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AN EVALUATION OF LANDFILL GAS MIGRATION AND A PROTOTYPE GAS MIGRATION BARRIER

Winston-Salem Department of Public Works

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This project provides a literature review of landfill gas generation and movement and the state-of-the-art of landfill gas control technology; a review of the explosion attributed to ignition of migrating landfill gas in the North Carolina National Guard Armory on 27 September 1969; the design, installation, evaluation and demonstration of a unique type of active gas barrier between the Link Road landfill and the Armory; and the development of guideline considerations for gas barrier design and detection of landfill gas migration hazards.

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under demonstration grant project S-801519 was written by
DEPARTMENT OF PUBLIC WORKS, CITY OF WINSTON-SALEM, NORTH CAROLINA
and ENVIRO-ENGINEERS INC. *and, with minor exceptions,*
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U.S. ENVIRONMENTAL PROTECTION AGENCY

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The completion of this project in essential fulfillment of most of the objectives originally conceived, despite the limitations which ensued (namely, the impracticality of obtaining definitive data adequate for comparative analysis at the sites available and the unforeseen modification of the Link Road landfill) is due in no small measure to the close liaison and assistance provided by EPA project representatives Keith Hanley and Truett DeGeare. They redirected the project to changing conditions and barrier design aspects to permit the development, design, installation and testing of a prototype gas barrier system.

The Winston-Salem project staff was most diligent in fulfilling its responsibilities, and strong support and invaluable assistance were provided by Joe H. Berrier, Director of Public Works, Pat Swann, Assistant Director of Public Works, and Robert H. Davis, Assistant Superintendent of Sanitation Division. A special note of commendation is due Frank Styers, whose intimate knowledge and understanding of gas-barrier principles and his familiarity with the Link Road site resulted in high-quality construction and performance of the gas barrier.

Acknowledgment is also due representatives of the North Carolina National Guard for their close cooperation, particularly Major James N. Stoneman.

Key personnel from Enviro-Engineers, Inc., an affiliate of Engineering-Science, Inc., who participated in this project were M. DeVon Bogue, Program Manager, and Dr. Bahman Sheikh. The overall program was conducted under the technical direction of Dr. Donald L. Feuerstein.

CHAPTER I

SUMMARY

The Department of Public Works, City of Winston-Salem, North Carolina, assisted by Enviro-Engineers, Inc., conducted a study of gas hazards associated with the Link Road landfill and nearby structures, particularly the North Carolina National Guard Armory, from August 1972 through June 1974. The study included a literature review of landfill gas generation and movement and of the state-of-the-art of landfill gas control technology; a review of the explosion attributed to ignition of migrating landfill gas in the Armory on 27 September 1969; the design, installation and evaluation of a unique type of active gas barrier between the landfill and the Armory; and the development of guideline considerations for gas barrier design and detection of landfill gas migration hazards.

The review of literature on landfill gas generation and movement indicated that information on this subject is sparse. The state-of-the-art of landfill gas control technology is limited in scope and application, consisting primarily of high-capacity active systems, installed after landfills were completed and developed without specific consideration of gas flow principles or conditions at the site of barrier installation. The review of the Armory explosion did not delineate any likely causes other than migration, accumulation and ignition in the Armory supply room of gases from the Link Road landfill.

The gas barrier system, designed, installed and evaluated at the Link Road site, was developed on a rational basis, considering the anticipated generation of gases in the landfill, gas permeability of the adjacent soils, gas flow principles and similar factors. The system incorporates a series of gravel-filled wells, each containing a perforated pipe and valve assembly. A header connects all wells to a small-capacity vacuum pump and vent assembly. The system is monitored by a gas analyzer console in the Armory, connected to a series of gas probes in the soil between the barrier and the Armory and in interior spaces, along with audible and visual alarms to indicate gas concentrations exceeding 25 percent of the lower explosive limit.

Testing of the installed system included measurements of gas concentrations on both sides of the barrier and the measurement of pressure profiles along and transverse to a section of the barrier. Combustible gas concentrations were reduced on the Armory side of the barrier to zero or near-zero levels within several weeks after pumping began, and have remained at these levels through June 1974 at minimal pumping rates. Ubiquitous negative pressure levels were established in the soil along and near the barrier shortly after pumping began and have been maintained throughout the test period. It would appear that the efficacy of the barrier has been demonstrated.

Although the program did not permit refined or detailed guidelines for the detection of gas hazards by simplistic procedures performed by landfill management personnel, general comments were derived based on project experience which may be helpful.

CHAPTER II

INTRODUCTION

PROJECT BACKGROUND

The degradation of buried solid wastes under anaerobic conditions results in the generation of methane gas which may migrate through the soil into areas peripheral to the landfill and accumulate in explosive concentrations. Methane is odorless and cannot be readily detected without special instruments; consequently, means are needed not only to determine the mode and extent of migration of landfill gas but also to provide systems to protect buildings and other structures from gas entry and accumulation. This report provides the results of a project to investigate an explosion attributed to accumulation and ignition of landfill gas at the National Guard Armory in Winston-Salem, North Carolina; to investigate gas migration characteristics; to design, install and evaluate a prototype gas barrier; and to provide criteria and design guidelines for gas barriers. The following sections describe background elements and project objectives.

Armory Explosion

On 27 September 1969, at about 8:40 a.m., a flash fire or explosion occurred in the supply room of the North Carolina National Guard Armory in Winston-Salem, North Carolina. Twenty-five guardsmen were injured and three died as a result of the accident.

The nearby Link Road solid waste landfill was considered to be the source of explosive gases, which were thought to have migrated through the soil and into the building. An account of the explosion, including a review of possible contributing factors, is presented in Chapter III.

Early Investigations

Following the explosion, a number of investigations were made in an effort to determine the cause of the incident, the potential for a recurrence, whether explosive gases were migrating from the landfill into neighboring areas through the soil and to evaluate the factors determining the migration and accumulation of gases from the landfill. Those investigations relating to the explosion are detailed in Chapter III.

The Winston-Salem Department of Public Works then sought the assistance of Enviro-Engineers, Inc. (EE), who had performed investigations of migration of gas from landfills in the Los Angeles, California area, to define and initiate a gas monitoring program at the Link Road landfill for the purpose of determining combustible gas concentrations and migration potentials.

Twenty gas sampling probe locations, with probes located at 1-, 10-, 25-, and 40-foot depths, were established around the northwest periphery of the landfill and around the Armory. The probes, patterned after those used by EE in the Los Angeles studies, were attached to plastic tubes leading to ground level where they could be connected to portable gas analyzers for direct reading of combustible gas in percent of the lower explosive limit or in percent by volume. Gas samples were also taken for gas chromatographic analysis. Gas concentrations were determined at those probes nearest the Armory once daily and at the remaining probes once weekly. (These initial monitoring probe locations are shown in Figure 5, Chapter III. In later investigations, additional probes were installed. Some were destroyed and others were not used in some of the investigations.)

Combustible gas concentrations in and near the landfill were at high levels throughout the surveillance period, and relatively high levels of combustible gas were noted in those probes located on the side of the Armory nearest the main body of the landfill. The probes nearest the supply room showed consistently high levels of combustible gas at all depths, and probes beneath the building slabs in the supply and assembly rooms showed combustible gas concentrations well above the lower explosive limit most of the time.

It was generally concluded that conditions existed wherein combustible gas (primarily methane) was being generated in the landfill in considerable quantity, that it was migrating through the soil to and beneath the Armory and that concentrations above the lower explosive limit could accumulate beneath or in the building, posing a likely hazard of recurrence of explosions if the Armory were reoccupied. (The Armory was vacated shortly after the explosion.) It was further concluded that safe beneficial occupancy and use of the Armory could not be resumed unless combustible gas concentrations near and beneath the building could be brought, and maintained, well below the lower explosive limit. The extent and results of early investigations are included in Chapter III.

Project Development and Funding

The Winston-Salem Department of Public Works, after discussions with U.S. Environmental Protection Agency (EPA) Solid Waste Program representatives, submitted, in January 1970, an application for a demonstration grant to conduct a study and demonstration related to the Armory explosion and to design and evaluate a gas barrier at the Link Road landfill.

After several revisions of the original proposal, which resulted in a considerable expansion of the total project, a grant award was made on 26 June 1972, and the project was initiated by EE to provide engineering consultation, design and evaluation functions. The project is more fully described in the following section and project findings are embodied in the succeeding chapters.

PROJECT OBJECTIVES

The project, as finally developed and funded, included four main objectives: (1) investigations pertaining to a review and report of the Armory explosion; (2) a review of the state-of-the-art of gas migration and gas barriers, a review of gas barrier technology and designs, the design of a gas barrier for installation at the Link Road site and its evaluation; (3) investigations of factors influencing gas generation and migration from landfills and development of procedures for detecting and evaluating gas migration in terms of management guidelines for land operators; and (4) establishment of design criteria for gas barriers.

A number of factors, including placement of new soil cover on the Link Road landfill, resulted in only partial fulfillment of a number of the tasks and in their termination, with EPA approval. It was not possible to accurately define the relationship of settlement, cell structure and cover thickness, climate and other factors with gas generation and migration; to evaluate effects of gas on vegetation as an indicator of gas potentials; or to establish a meaningful "checklist" technology for landfill operators. It appears that achievement of these objectives could best be fulfilled at a landfill where the various parameters could be more accurately measured rather than at a completed landfill. The barrier design and evaluation was reoriented, with EPA approval, toward the design and testing of a low-flow barrier system rather than the combined high-flow and gravel-trench system originally conceived. This revision has resulted in the development, evaluation and demonstration of new technology in gas barriers.

The project objectives listed below are those pursued in the final project to completion or to a point where meaningful information or observations were possible.

Investigation and Report of Armory Explosion

This objective included the accumulation and assembly of all known data, facts, accounts and reports on the occurrence and aftermath of the explosion; assembly and review of all investigations and reports of conditions at the site before and after the explosion; determination and description of the development and operation of the landfill; a review of similar incidents elsewhere; an investigation of the landfill site and the Armory to document features which might have contributed to the migration of gases and their accumulation and ignition in the Armory; a determination, if possible, of the cause of the explosion; and preparation of a full account of the explosion, investigations and conclusions, if any. Chapter III presents a complete account of the fulfillment of this objective.

Evaluation of Factors Related to Gas Generation and Migration

This objective included a review of the technical literature on gas generation and movement to establish those parameters which should be investigated and which would be most applicable within a checklist methodology for landfill operators in assessing gas migration and hazards. Other activities included the selection and characterization of appropriate test landfills; the design and installation of monitoring systems for combustible gas concentrations, settlement, vegetation effects and climatological factors; collection and analysis of data; development of gas monitoring techniques; and development of a checklist and rating system. These efforts were only partially successful, and effort in achieving this objective was reduced with EPA approval. Consequently, the gas monitoring techniques and the checklist procedure are of a very preliminary nature. Findings are presented in Chapter IV, and recommended techniques are given in Chapter IX.

Review of State-of-the-Art in Gas Barrier Design

The objective included a review and summary of the technical literature and analysis of the design aspects, functioning and application of existing or new technology to the conditions of the Link Road landfill. The review included both active and passive systems and systems incorporating features of both, plus assessment or development of new technology, including high-flow and low-flow systems. A summary and analysis of the state of the art is provided in Chapter V.

Data Accumulation and Investigations Related to Barrier Design

The task required collection of data for design purposes, including gas production potentials, soil characteristics and gas permeability, area to be protected, cost, technological and construction considerations, and monitoring systems. Findings are presented in Chapter VI.

Selection and Design of Gas Barrier

The objective required selection of the most appropriate gas barrier and preparation of detailed design drawings and specifications, including cost estimates and bid document information. The details of fulfillment of this objective are presented in Chapter VI.

Gas Barrier Installation

The objective included selection of a contractor, equipment procurement and construction supervision. Details are included in Chapters VI and VII.

Monitoring Program

Throughout the project, gas concentrations were monitored at the Link Road landfill and at two other landfills (not reported herein) in accordance with the needs of the various objectives. Monitoring included the installation of gas probes, the periodic determination of gas concentrations using a portable combustible gas detector and analysis of samples by gas chromatography. In addition, records were collated on rainfall and other climatological data. Monitoring was done on a relatively continuous basis at the Link Road landfill and was revised (following selection of the barrier design) to provide base-line data and performance-evaluation data for the barrier. Monitoring programs are described in Chapter III and in Chapters VI through IX.

Gas Barrier Evaluation

Prior to installation of the gas barrier, gas probe layout and installation was devised, along with a detailed program for determining barrier performance. The evaluation included monitoring of gas flows in various parts of the system, determination of pressures in the soils adjacent to the barrier and determination of gas concentrations on both sides of the barrier and inside the Armory by means of portable gas analyzers, gas chromatography and the installed automatic monitoring systems. Evaluation of gas barrier performance is given in Chapter VIII.

MANAGEMENT OF THE STUDY

A work plan was developed wherein the accomplishment of the various tasks required to fulfill each objective was subdivided into subtasks, and responsibilities were assigned to the Winston-Salem project staff and to EE. For the most part, data collection was performed by the Winston-Salem project staff in accordance with EE recommendations. Data analysis was performed primarily by EE. Technology reviews, barrier selection and design were an EE responsibility, along with development of barrier evaluation programs. Barrier installation and development of barrier performance data were Winston-Salem responsibilities, whereas analysis of performance data and development of design guidelines were done by EE. The account of the Armory explosion was largely a Winston-Salem staff effort with EE's major input being directed toward interpretation of documented investigations and specific further investigations to complete a technical review of the factors possibly related to the incident. EE had the major responsibility for developing and preparing the technical report.

CHAPTER III

AN ACCOUNT OF THE EXPLOSION IN THE WINSTON-SALEM NATIONAL GUARD ARMORY

ACCOUNT

On 27 September 1969, at approximately 8:40 a.m., a flash fire or explosion occurred in the supply room of the North Carolina National Guard Armory at 2000 Silas Creek Parkway (formerly Link Road) in Winston-Salem, North Carolina. Of approximately 25 Guardsmen injured in and near the Supply Room, 12 were seriously injured, seven of whom are now partially or totally disabled. Three Guardsmen died as a result of burns or subsequent complications.

The National Guard Armory was built in 1962 adjacent to the City's operating solid waste landfill, whose continued operation was a condition of the deed. In addition to the Armory, the National Guard utilized adjoining landfilled property for parking and servicing a large fleet of supply vehicles, including large-capacity fuel tankers. Other National Guard structures included a garage/repair building, a small shed and an underground fuel-storage tank in the parking area, and a prefabricated steel storage building constructed on a slab placed over a landfilled area to the rear of the Armory. The Armory was built on a six-inch reinforced concrete slab and, except for the central drill-hall area, is of one-story concrete-block construction. A two-story addition to the building, built by the City in 1965, housed Winston-Salem's Police Academy. The slab was poured over four inches of crushed stone. The site was prepared by leveling existing topography. No portion of the building extends over a landfilled area and closest proximity to the landfill (about 30 feet) is at the rear of the building. Prior to placing foundations, it was found that soil conditions at the rear of the buildings did not provide adequate bearing capacity; consequently, spread footings were used to a depth of six feet along the rear of the building. No mechanized ventilation system was provided for the main building.

Other structures nearby on land of or adjacent to the Link Road landfill include an abandoned abattoir (now used for fire training purposes), a fire training tower and a peripheral road constructed around the fire training area, developed by the City for Fire Department use. The fire training tower is built on a landfilled area as is the peripheral road. Fire hydrants are supplied by a looped eight-inch water main crossing beneath the vehicle storage area from Silas Creek Parkway.

Utility structures include water and electrical services to the Armory, a sanitary sewer serving the garage and Armory, building sewer and drains and a 72-inch storm drain constructed through the landfill and discharging to Salem Creek. The storm drain was emplaced during landfill construction. Street drains from the fire training area, the entrance road and paved areas enter the storm drain.

Figure 1 provides general details on the Armory, the nearby landfill and associated facilities. Figure 2 shows the boundaries of the landfill and structure and Figure 3 shows final landfill topography (prior to placement of additional cover in July 1973).

The Link Road landfill was initiated in 1949 when the City's onsite incinerator was closed and was near completion in 1969 when the Armory explosion occurred. The present vehicle storage area is placed over the area formerly used to landfill incinerator residue. Dead animals and wastes from the abattoir were disposed in trenches close by. No other segregation of wastes was practiced (except surface composting of leaves and vegetative trimmings) and wastes deposited throughout the remainder of the fill include intermixed domestic, industrial and commercial wastes. In general, wastes were placed in an organized fashion, compacted to the

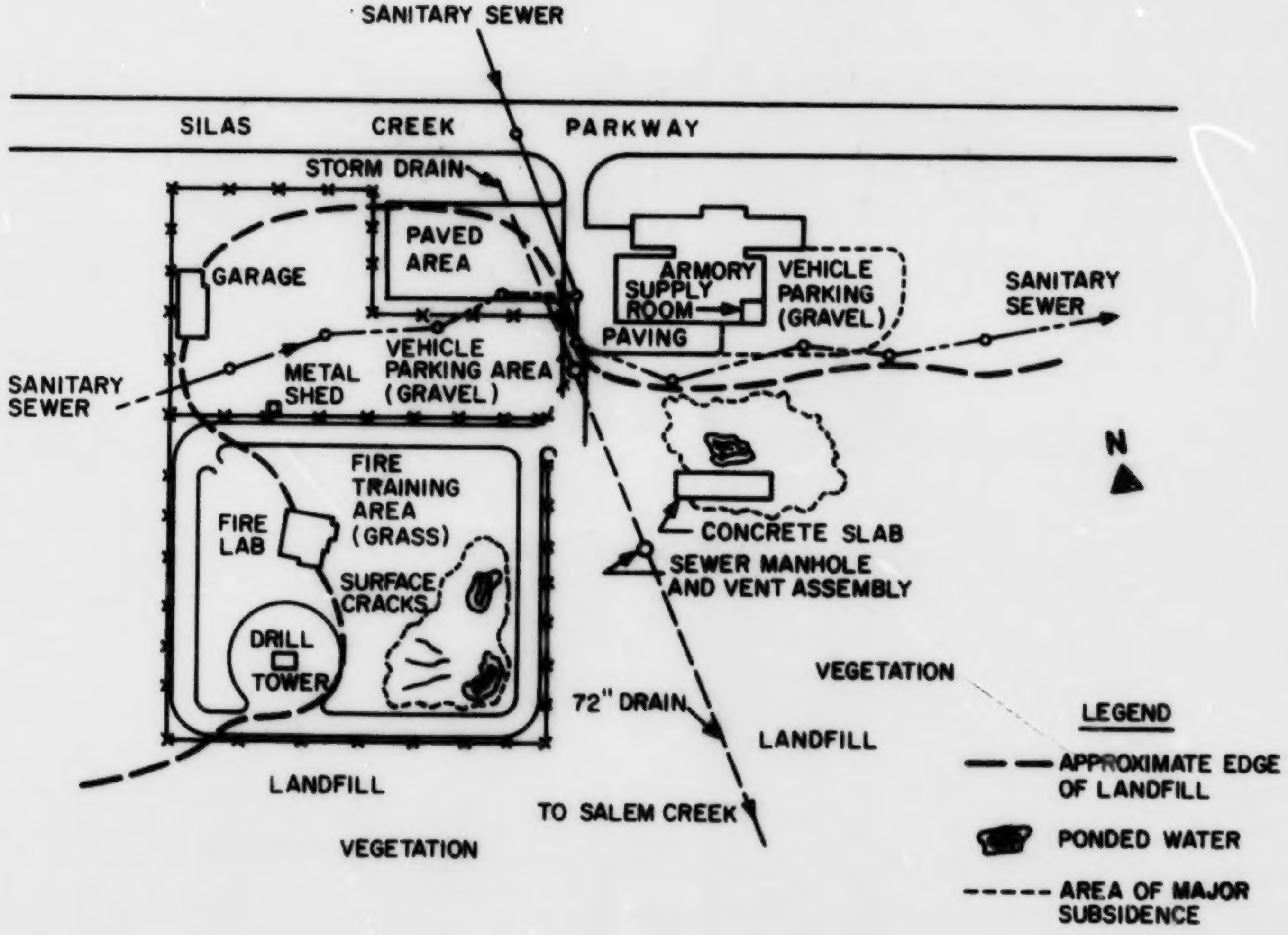
SANITARY SEWER
SILAS CREEK PARKWAY
STORM DRAIN
PAVED AREA
GARAGE
ARMORY SUPPLY ROOM
VEHICLE PARKING (GRAVEL)
SANITARY SEWER
PAVING
SANITARY SEWER
METAL SHED
VEHICLE PARKING AREA (GRAVEL)
N
FIRE TRAINING AREA (GRASS)
FIRE LAB
SURFACE CRACKS
DRILL TOWER
CONCRETE SLAB
SEWER MANHOLE AND VENT ASSEMBLY
VEGETATION
72" DRAIN
LANDFILL
LANDFILL
TO SALEM CREEK
VEGETATION
LEGEND
APPROXIMATE EDGE OF LANDFILL
PONDED WATER
AREA OF MAJOR SUBSIDENCE

Figure 1: National Guard Armory and associated structures, 1972

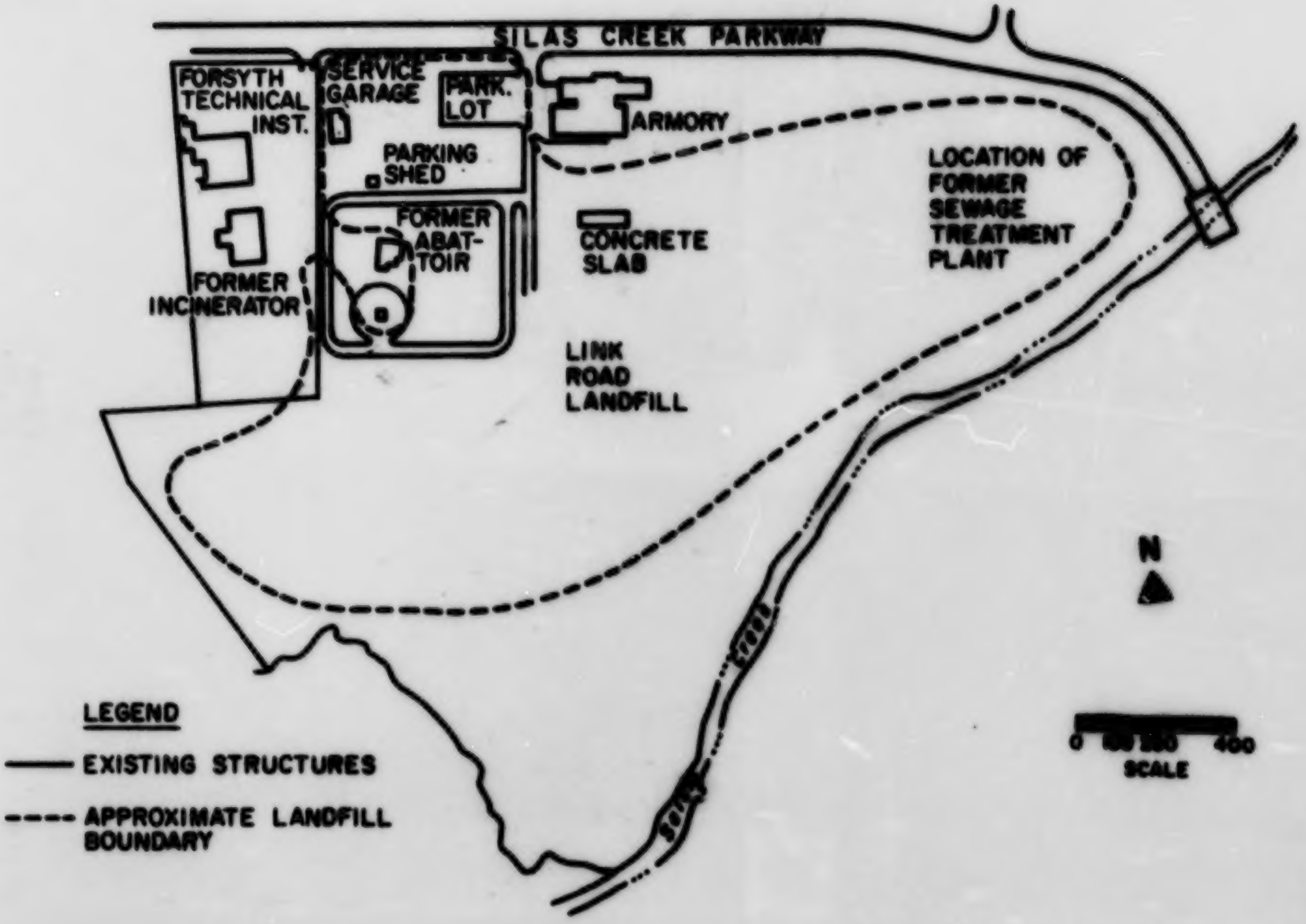
SILAS CREEK PARKWAY
FORSYTH TECHNICAL INST.
SERVICE GARAGE
PARK. LOT
ARMORY
PARKING SHED
FORMER ABAT-TOIR
FORMER INCINERATOR
CONCRETE SLAB
LINK ROAD LANDFILL
LOCATION OF FORMER SEWAGE TREATMENT PLANT
N
0 100 200 400
SCALE
LEGEND
EXISTING STRUCTURES
APPROXIMATE LANDFILL BOUNDARY

Figure 2: Link Road landfill and associated structures

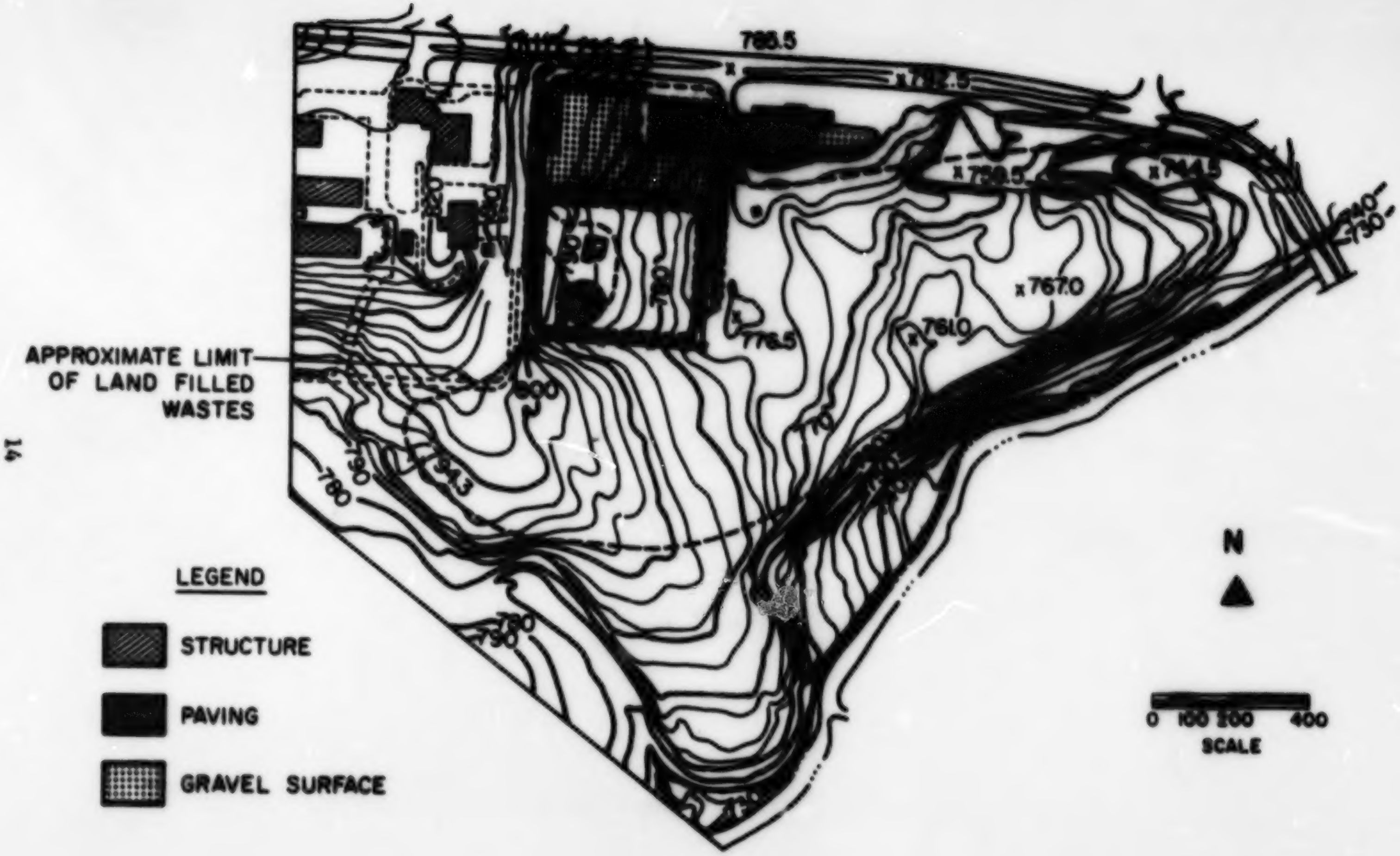
785.5
x 772.5
x 759.5
x 744.5
740
730
x 767.0
x 761.0
776.5
780
770
800
820
790
780
794.3
790
780
APPROXIMATE LIMIT OF LAND FILLED WASTES
LEGEND
STRUCTURE
PAVING
GRAVEL SURFACE
N
0 100 200 400
SCALE

Figure 3: Final topography of the Link Road landfill site, 1972

best of ability of equipment provided and covered with compacted soil cover, if not daily, at frequent intervals. Operation of the site, while perhaps not in strict accordance with high standards set for sanitary landfills today, was equivalent to or better than operation of its contemporaries. Depth of the landfill ranges from 10 to nearly 40 feet in places. Immediately back of the Armory, wastes were packed along a steep natural bank (extreme settlement occurred and is continuing to occur at this location). The landfill is reported to have incorporated a high ratio of soil cover to wastes deposited. Most of the bulk of the landfill is saturated from groundwater and surface water. Total quantity of wastes deposited is estimated at 1.4 million cubic yards. Figure 4 shows typical cross sections through the landfill.

In the summer of 1965, a welder installing part of the storm drainage system near the Armory received minor burns in a flash fire. In November of the same year, a fireman working near one of the street drains in the fire training area dropped a lighted match into a manhole and received minor burns in the resulting minor explosion. In December 1965, the Guard's Executive Officer reported a flash fire while welding downspouting on the Armory's roof drain system which he was connecting to an underground drainage system extending into the filled area back of the Armory. The Fire Department determined presence of combustible gas in the abattoir but none in the Armory. In 1966, representatives of the Federal Solid Waste Program investigated conditions in the fire training area and confirmed methane in the storm drains. In July 1966, following complaints of strong odors from the landfill, a blower was installed in a brick building, surmounted by a tall vent stack, over a large manhole in the storm drain to the rear of the Armory. This venting system was operated intermittently thereafter and was apparently effective in dispersal of gas and odors. During these early episodes, investigations centered around accumulation of combustible gases in sewers, a condition not uncommon to sewers, though more common to sanitary sewers than to storm drains. No detailed investigations were made to determine occurrence or extent of gas accumulation in the Armory.

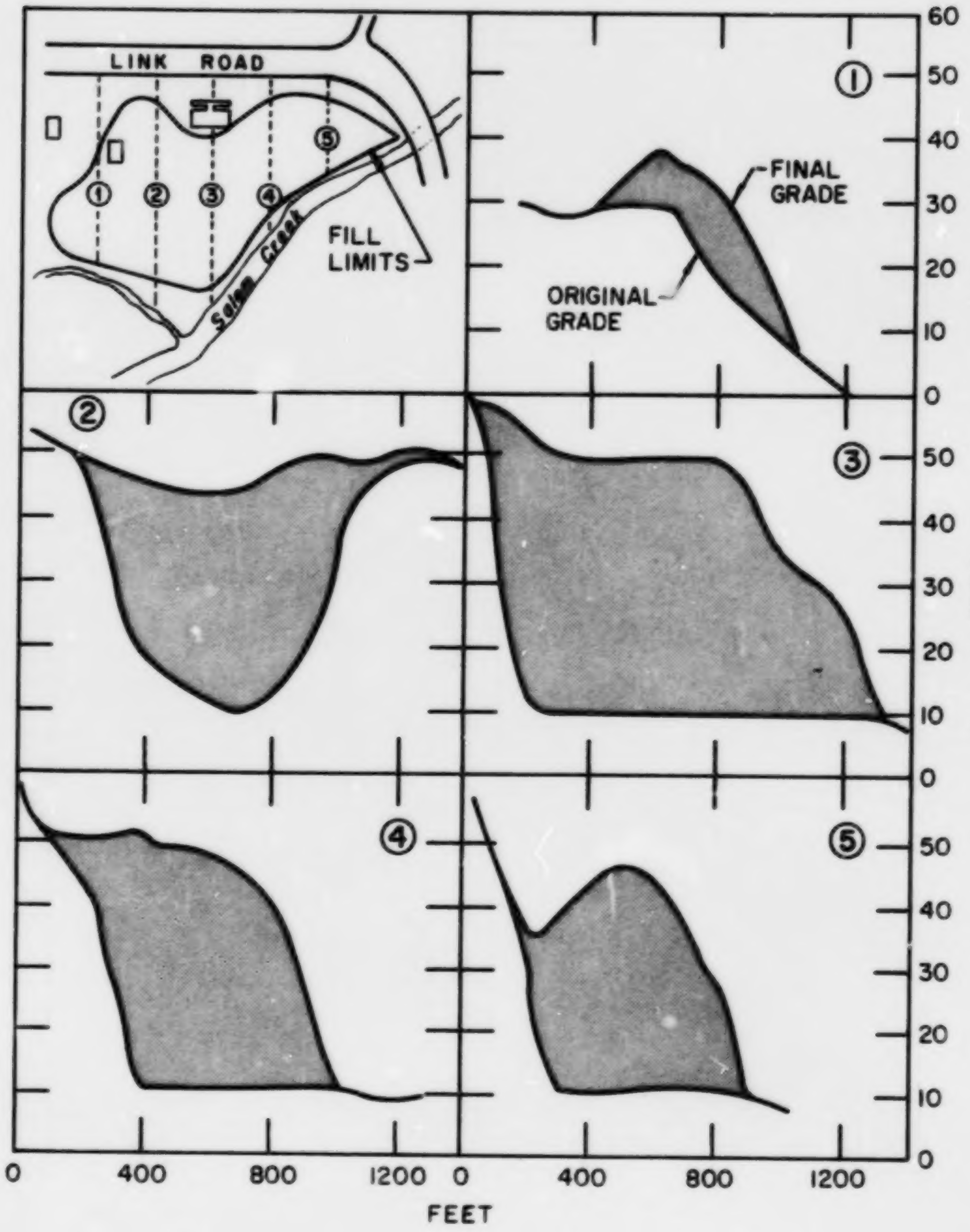

Figure 4: Cross-sections through completed Link Road landfill, 1972

Only a week or so before the explosion occurred, three to four feet of additional cover had been compacted over the landfill just back of the Armory, where extensive settlement had occurred. The Guard subsequently dismantled and removed the prefabricated building nearby, due to extensive deformation of the building slab caused by settlement of the landfill in this area.

On 26 September 1969, the day before the tragedy, City representatives met with Guard representatives to investigate the occurrence of "odors or gas" from the arms storage vault off the Armory supply room. No source of gas, defective systems or other causes were noted. Arrangements were made to have the Fire Department check out the vault (after being closed several days) with portable gas detection equipment the following week. Since the vault would be opened during drills, the Guard proceeded with scheduled drills. The explosion occurred the following morning.

Immediately following the explosion, it was conjectured by some that the "blue flame" explosion or fire was caused by ignition of gas migrating from the landfill and accumulating in the vault or supply room. Investigations did not reveal presence of petroleum products or flammable materials in the supply room or vault, nor was an ignition source definitely established. It is presumed that one of the Guardsmen lit a match, despite posted "No Smoking" regulations.

The explosion lifted the roof of the supply room at least six inches at the southeast corner. Windows were broken, but it was not known whether they were broken by the occupants or from the force of the explosion. The rear wall and ceiling were blackened and scorched, but most of the stored materials (such as blankets) were undamaged. A one-half inch horizontal separation between the rear wall and the floor slab was noted following the explosion.

Combustible gas sampling in the supply room, drill hall and pistol range shortly after the explosion, using a portable combustible gas indicator, revealed combustible gas concentrations near or above the lower explosive limit* (LEL) only at cracks in the slab. In soils outside the Armory, readings were above the LEL. It was thought that soil saturation by recent heavy rains prevented landfill gas from venting through the landfill cover, thereby increasing lateral gas migration while lack of ventilation in the building may have contributed to gas accumulation in the supply room. Subsequent readings on 6-9 October 1969 were inconclusive, but seemed to indicate a significantly higher concentration in the vault than in the supply room (but no concentrations were noted above the LEL).

Gas sampling was done in nearby sanitary sewers and storm drains on 9-10 October and 21 November 1969. Whereas high combustible gas concentrations were noted in manholes near and behind the Armory in the early tests and petroleum vapor was reported in two of the manholes, there was no conclusive evidence of gasoline or other petroleum vapors entering the Armory from the sewers, and all combustible gas concentrations had diminished by late November 1969.

A network of 20 holes was drilled 30- to 40-feet deep around the Armory in 1970, and gas sampling probes were inserted at 1-, 10-, 25- and 40-foot depths. The probes, whose locations are shown on Figure 5, were connected to plastic tubes leading to the surface from which combustible gas concentrations were determined periodically with a portable combustible gas detector. Subslab sampling points were established by drilling holes through the floor slab in the drill hall and supply room. Combustible gas concentrations in the range of 30 to 40 percent by volume were recorded in the exterior probes over a period of many months. Concentrations in excess of the LEL were consistently recorded below the building slab. This sampling program verified that combustible gas from the Link Road landfill was migrating to and beneath the Armory, presenting a continuing hazard of gas accumulation and explosion. Concern about this situation prompted interest in developing and demonstrating a gas barrier between the landfill and the Armory.

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*For methane, the LEL is four to five percent by volume in air.

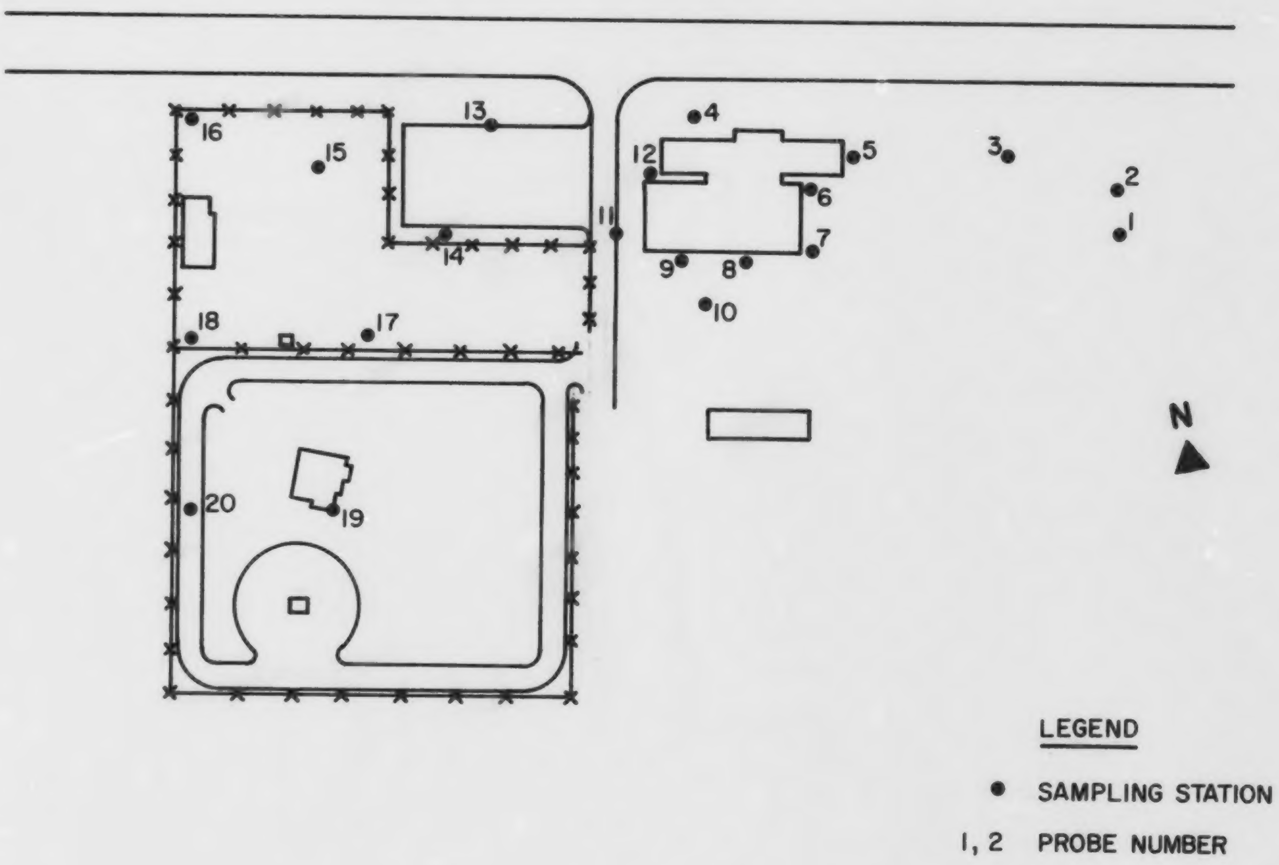
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Figure 5: Initial gas monitoring stations, 1970-1971

The Armory was vacated shortly after the explosion and since has remained vacant. The landfill was completed in March 1970 but continued use has been made of the fire training center and the Guard's vehicle storage and maintenance area. Wild vegetation has grown over most of the landfill surface. Except for periodic monitoring of combustible gas concentrations, little activity was conducted on site until August 1972, when investigations began related to studies of gas migration and development of a gas barrier. A portion of these investigations was directed toward a review of the Armory explosion and to possible causes.

FINDINGS

During the placement of probes in the landfill for combustible gas concentration evaluations in 1973, it was found that high moisture conditions occur throughout the landfill. Combustible gas measurements indicate that the gas migrates through the soil a considerable distance from the landfill boundary and occurs beneath the Armory in explosive concentrations. Investigations indicated that the soil cover, though variable in consistency and thickness, is relatively porous, but that saturation of the surface layers by rainfall may increase lateral migration. The landfill is continuing to settle unevenly, particularly in a large area immediately back of the Armory and in an area on the east side of the fire training area (see Figure 1). In the summer of 1973, three to four feet of new soil cover was placed over the upper portion of the Armory. This new soil cover places additional weight on this portion (which continues to subside) and may further reduce venting of gas through the cover or intensify local gas migration through adjoining soils.

Analysis of soils along the line of the barrier indicated considerable variation in the soil's gas permeability along the landfill periphery, with the greatest permeability being noted back of the Armory. In early tests of the gas barrier in 1974, rapid gas flow was noted into three of the barrier's suction wells, located about midway in the vehicle storage area, indicating local areas of high gas permeability in the nearby soils. Porous incinerator residue underlies this area.

Gas flow toward the Armory appears to be greatest immediately to the rear of the Armory, where the landfill periphery is closest and where major settlement is continuing. Significant combustible gas concentrations also occur on the west side of the Armory, indicative either of relatively long-range but attenuated gas migration from the main body of the landfill or of moderate gas flow from wastes landfilled in the incinerator-residue area.

In 1973, a ditch was dug around the southeast corner of the Armory to a depth of about eight feet in order to determine if direct channels for gas migration existed between the landfill and the Armory in this area. Examination indicated that several types of relatively coarse, sandy soils were intermixed, with discrete lenses of sandy-micaceous material ocurring throughout. No direct conduit or obvious avenue for ready migration of gases was noted. Tests on the soil did not indicate presence of petroleum products. At the same time, field tests were made which indicated that building drains were functioning properly. It was noted that tile drains, formerly connected to roof-gutter downspouts, had openings near the building which would permit venting of any gases entering the drains before they reached the building. There was no connection between roof drains and the Armory interior.

Inquiries to the National Guard regarding possible spillage of gasoline into sewers on nearby soils, with likely entry into the Armory, did not substantiate this possibility.

In summary, the exact cause of explosive gas accumulation in the supply room or vault and its subsequent ignition has not been determined. It does not appear that utility gas or petroleum-vapor sources were likely. No explosive gas, other than combustible gas migrating from the landfill, was discerned and the Armory was reasonably well-protected from accumulation of gases from normal sources. Combustible gas was likely migrating from the landfill through adjoining soil to and beneath the Armory prior to the explosion, but its presence or hazard potential had not been confirmed. Early assumptions that combustible gas concentrations were confined to sewers were reasonably valid, in the light of extant knowledge and practice. Although operation and construction of the Link Road landfill resulted in conditions contributing to extensive gas production and migration, the nature and potential hazards of gas migration were not then well known. The landfill was operated in a manner common to landfill practice prevailing at that time.

The Armory explosion has highlighted (unfortunately with tragic aftermath) the extreme importance of recognizing the hazardous explosion potentials from landfill gas migration possibly resulting from operation of solid waste land disposal sites. Measures to minimize gas production and migration potentials during and after landfill operation are in order, along with the protection of structures nearby from gas accumulation by structural features and by active or passive gas barriers. Such measures are included in modern guidelines for sanitary landfill design and operation.

Litigation following the Armory explosion has apparently been settled. Tests on the gas barrier have thus far indicated favorable results. Gas concentrations between the barrier and the Armory have been reduced to zero or near-zero levels by operation of the gas barrier. If, after a suitable period of operation, the gas barrier remains as effective as the preliminary results have indicated, and the barrier system is properly operated, regularly monitored and constantly maintained at specified operating levels, normal use and occupancy of the Armory should be possible.

CHAPTER IV

REVIEW OF GAS GENERATION AND MOVEMENT FROM SOLID WASTE LANDFILLS

LITERATURE REVIEW

The paucity of information on gas generation and movement from solid waste landfills is attested to by only brief mention in a principal solid waste disposal reference (Reference 1) and the listing of only 48 articles in the most recent bibliography on the subject (Reference 2). Many of the articles are of a nontechnical nature and, in many cases, discussions of gas generation and movement are only a small part of the article listed. Only a few are based on scientific measurements over a significant period of time, and several of those containing specific data are based on observation of simulated landfills, on test refuse cells or on laboratory-scale experiments. The most informative of the early articles, based on field studies, was that reporting studies related to groundwater and to carbon dioxide production from landfills, conducted by or for the California Department of Water Resources, the California Water Pollution Control Board and the California State Water Quality Control Board. Studies of gas explosion episodes were limited in thoroughness or scientific approach; the most extensive report being of an explosion in an abandoned power substation in Atlanta, Georgia, which was being converted to a recreation facility adjacent to a landfill. An extensive study by Los Angeles County included a review of gas production and movement at 10 landfills in the Los Angeles area and extensive laboratory studies to determine diffusion coefficients for landfill gas in a variety of soils (Reference 3). The study also presented design and construction criteria for buildings on or near solid waste landfills.

Studies of pilot landfills or refuse cells in southern California (References 4, 5, 6 and 7) have contributed considerable information on gas production and migration. Most of the reported work on gas generation and movement has been undertaken in recent years (i.e., since 1954); the earliest article was published in 1940.

The literature review was supplemented by field inspection and review of information on existing solid waste landfills in the Los Angeles, California area where a number of gas migration studies or observations have been made and where gas barrier systems have been installed.

GAS GENERATION FROM SOLID WASTE LANDFILLS

In the early stages of solid waste decomposition in a landfill, decomposition takes place through processes which utilize the initial supply of oxygen entrained in the wastes. In the first six months to a year, carbon dioxide predominates. Principal gases produced are carbon dioxide, hydrogen, nitrogen and methane. Carbon dioxide and methane make up over 90 percent of the total gas produced (Reference 8). Hydrogen sulfide may be produced in areas where salt water is in contact with the refuse. As the entrained oxygen supply diminishes, anaerobic decomposition ensues and an increasing amount of methane is produced while other gas production diminishes. Significant methane production may occur within six months to a year, and production may continue over long periods of time. The production of gases depends on a number of factors, including the amount of oxygen available, the organic content of the solid wastes, particle size and degree of compaction and the amount of moisture available. In general, high organic content and moisture will increase gas production. Smaller particle size (by exposing more of the refuse to bacterial action) may have a similar effect. There are some indications that densely compacted refuse will decompose at a slower rate than loosely compacted refuse and that gas production may be prolonged in densely packed landfills (Reference 7). Several studies of gas production have indicated that from very moist or saturated "normal" domestic refuse, carbon dioxide may be produced in quantities of about 0.2 cu ft/lb, whereas from the same type of refuse which is relatively dry, the production is only about 0.04 cu ft/lb (Reference 9). In a sealed test chamber of mixed refuse, 2,027 cu ft of decomposition gases were produced from 73 cu yd of refuse over 906 days, or about 28 cu ft/cu yd (Reference 7). In a similar test, over a 200-day period, gas production was approximately 28 cu ft/cu yd of refuse, or about 0.04 cu ft/lb (Reference 7). Theoretically, a pound of refuse can produce 2.7 cu ft of carbon dioxide and 3.9 cu ft of methane (Reference 10). How much of this potential production will be realized in a particular landfill over a given period of time will depend on a number of factors which aid or hinder gas production, and the variations in production will be largely dependent on variations in these factors.

Anaerobic conditions may occur within a month after wastes are buried (Reference 11). Dry landfills apparently produce much less gas than those which are initially or subsequently saturated with moisture. Moisture additions to a landfill can reinitiate or increase carbon dioxide and methane production. Under such conditions, once initiated, methane production may continue for a long period of time.

GAS MIGRATION FROM LANDFILLS

In studies of migration of decomposition gases from landfills (References 4, 8, 12, 13 and 14), it has been noted that carbon dioxide and methane migrate upward and downward as well as laterally through surrounding soils. Most of the gas produced will migrate upward through soil cover. Field observations have reported explosive concentrations consistently as far as 600 feet from a landfill (Reference 15).

Field observations in a study of a landfill in southern California (Reference 12) indicated that carbon dioxide moved vertically through the soil cover at more than 10 times the rate it moved downward or laterally through adjacent soils. Other studies indicate that 18 to 24 times the quantity of carbon dioxide and methane, respectively, pass through the cover than into the surrounding soil (Reference 13). Carbon dioxide movement rates ranged between 0.22 and 0.8 ft/day vertically and between 0.24 ft/day and 1.4 ft/day horizontally (in undisturbed alluvial soils) in one study (Reference 9) to vertical and horizontal velocities of 0.22 ft/day to 0.24 ft/day in another (Reference 14).

Little is known about gas migration within a landfill. In landfills where well-compacted waste and cover does not prevail or where settlement, groundwater intrusion or fires have caused destruction of cell integrity, gas will likely migrate through voids or channels throughout the mass, perhaps towards a section of the landfill's periphery where localized (rather than general) gas migration may occur. Numerous instances have been noted where methane or other gases issue from surface cracks in landfills in large quantity and at considerable velocity. Maintenance of a gas-permeable cover or other means of venting would appear to be most important in insuring that lateral landfill gas migration is minimized. Impermeable sealing of a landfill surface at any time will likely cause a prompt increase in lateral gas migration (Reference 16). Even if a landfill has been in place for many years and decomposition of early-deposited refuse is in an advanced stage (with theoretically declining gas production rates), gas migration controls should consider characteristics of the more recently deposited wastes, wherein gas production and migration potentials may be highest. Critical areas of a landfill in terms of gas migration would likely be those where the moisture content is highest, where highly organic wastes were deposited (these are often concentrated in one area of the landfill, commonly with minimal compaction or cover) and areas where the landfill surface may be most impermeable.

In addition to the general gas migration characteristics of a landfill, it is apparent that local variations in gas production and migration occur, perhaps related to reduced permeability of soil cover due to precipitation, settlement or other phenomena. No long-range correlation of gas production and migration of landfill gases with precipitation has been documented, but field observations have indicated a general increase in gas migration following extensive precipitation. Monitoring of gas concentrations related to gas control barriers has indicated daily and periodic fluctuations or "excursions" of gas concentrations both above and below the average. Consequently, gas migration is likely to be extremely variable and control systems should be based on theoretical maximum potentials for gas production and migration.

HAZARDS DUE TO LANDFILL GAS MIGRATION

The principal hazard from migrating landfill gas is likely to be from methane. It has a relatively high production rate in comparison with other gases, it has a tendency to migrate laterally with greater facility than other gases when venting is impeded and it has a long-term production potential from landfills. Its explosive hazard and the inability to detect the presence or concentration of methane without instruments further emphasize its prime importance among the migrating landfill gases. The tendency of carbon dioxide to migrate downward to groundwater and to acidify it increases the corrosivity of the water. Methane, by contrast, is relatively insoluble in water. Maximum production of carbon dioxide from a landfill is relatively short-lived, in comparison with methane production. Hydrogen sulfide, because of its noxious odor, is relatively easily detected and is produced primarily in those relatively few landfills in contact with sulphate-containing sea water.

Relatively few occasions of explosions or other tragic consequences from migration of landfill gases have been reported, and only a couple have been investigated closely. A survey of 208 counties in 1965 indicated that only 21 percent had built on landfills. In these cases, many of the structures were plagued with settlement and gas problems (Reference 17). Fires in San Francisco's waterfront landfill were attributed to landfill gas (Reference 18). A fire in a manhole of a sewer built through a landfill near Knoxville, Tennessee occurred in 1947, within two weeks after the landfill was sealed with soil cover (Reference 16). At a large landfill near Seattle, Washington, pipes inserted through the soil cover were used to vent and burn off escaping gases and to partially eliminate odors (References 19 and 20). In the New York City area, gas accumulations in a sewer near a landfill were noted, and an explosion occurred in a small building situated on another landfill. More recent explosions include one at a warming hut at an above-ground sanitary landfill converted to a ski slope, an explosion in a former power substation being converted to a recreational facility next to an active landfill in Atlanta, Georgia (Reference 21), and the tragic explosion in the Winston-Salem, North Carolina National Guard Armory, built close to a landfill just being completed. The latter two episodes resulted in five deaths and in injury to 12 building occupants. In the Atlanta incident, methane gas accumulated in the building from landfilled refuse placed against and under the building and was ignited by a workman installing natural-gas heating facilities. Ignition of leaking natural gas from the gas facilities was ruled out as a cause of the explosion. In the Winston-Salem incident, early flash fires in sewer lines near the landfill had been attributed to gas migration from the landfill, but gas migration beneath the Armory had not been suspected. Following the explosion, presence of methane in the soil next to the building and beneath the building's floor slab was detected in explosive concentration. These and later investigations, reported in Chapter III of this report, failed to indicate a source of explosive gas other than combustible gas from the landfill. The influence of a large storm drain through the landfill, either as a channel for combustible gases to the Armory or as a contributor of water to the landfill, was not demonstrated, Monitoring of gas probes around the site in recent years indicates the continued generation of combustible gas and its migration to the vicinity of the Armory in explosive concentrations.

Most of the explosions have been attributed to accumulation and ignition of methane. Perhaps as a result of these other hazardous incidents, construction of buildings on or near landfills has apparently dwindled or such development is done with appropriate precautions.

OBSERVATIONS OF GAS MIGRATION AT WINSTON-SALEM

Early investigators attributed the accumulation of combustible gas in the Armory just prior to the explosion to an antecedent heavy precipitation, which reduced venting through the landfill cover with a resultant increased lateral migration, and to a lack of building ventilation. Gas permeability measurements of soil samples, taken relative to the gas barrier recently constructed, indicate that the peripheral soil is generally permeable to gas flow with highest permeability in the soils near the supply room, where the explosion occurred. Other possible influences include extensive settlement near the landfill edge nearest the Armory and subsequent additional placement of cover soil (shortly before the explosion).

It was not possible to make field measurement of gas generation rates or the relative effects of cover type, thickness or settlement on gas flow. It was determined, however, that high moisture occurs throughout the landfill and that it was actively producing combustible gas, which migrates readily through the surrounding permeable soils.

A more detailed account of observations and findings is presented in Chapter VIII.

CHAPTER V

STATE-OF-THE-ART IN GAS CONTROL TECHNOLOGY

INTRODUCTION

Relatively little investigative work has been performed and reported in the literature concerning the generation and movement of decomposition gases from sanitary landfills. Nevertheless, uncontrolled migration of decomposition gases from a landfill is recognized to be capable of posing a great threat to its environs due to pollution of groundwaters, damage to vegetation or the hazards of gas explosions. Only in recent years have active measures been undertaken to investigate and provide means for controlling the movement of decomposition gases from landfills. The limited literature on the subject of gas control measures makes reference to procedures which should or could be utilized to mitigate the problems of gas migration, but it contains very little reference to the actual means for achieving the desired results. This is probably due in large part to the experimental nature of the art of gas control technology. Testing and evaluation of the various control methods are still in progress in different parts of the country, and definitive conclusions are yet to be formulated. In general, detailed information on design and operation of gas control systems is lacking in the literature, mainly because this area is a recent addition in the field of landfill design and utilization.

GAS CONTROL SYSTEMS

This section contains information on gas control systems known to have been installed, mainly in the western United States, either for experimental purposes or in attempts to eliminate existing problems at particular sites. Gas control systems can be categorized into two major subsystems--pre-construction systems and post-construction systems. The pre-construction systems consist of measures that are incorporated into the design of the landfill to mitigate the movement of gases from the landfill. Integrated design measures taken to prevent the entry of gases into structures constructed on or adjacent to landfills are also included under the heading of pre-construction systems. Post-construction systems include all of those facilities which are designed and constructed after completion of the landfill or construction of structures on or near the landfill. Post-construction systems are developed as a solution for the problems created by uncontrolled landfills. Most gas control systems in existence today are of the latter type.

Pre-Construction Systems

Pre-construction systems are relatively recent innovations and their development has come about as a result of the increased awareness and knowledge on the hazards of landfill-generated gases. Various gas control methods may be utilized in the pre-construction stage. These methods are classified as "permeable methods" and "impermeable methods." Some permeable methods include the use of gravel vents or gravel-filled trenches to provide a more permeable path for the escape of gases from the landfill to the atmosphere. In this fashion, decomposition gases are intercepted and prevented from migrating beyond the limits of the fill. Other permeable methods consist of a system of gravel-filled trenches and/or wells, with vent pipes and collecting laterals inserted in the trenches and the wells for conveyance of gases out and away from the fill and adjacent structures.

Impermeable methods are based on the use of natural or synthetic barrier materials to prevent gases from migrating beyond the fill limits. A venting system is usually utilized along with the physical barrier system in order to prevent the buildup of positive gas pressure within the confines of the fill. Such venting would particularly be required if the surface of the landfill is later sealed by paving or by the use of some other impermeable cover material. The barrier system may consist of clay, synthetic membrane, concrete, asphalt or other bituminous material.

It has been suggested (Reference 22) that the most common, and possibly the most practical, impermeable barrier method involves the use of compacted clay, either as a liner in the bottom and sides of the fill or as a curtain wall to block underground gas movement. It was concluded from laboratory experiments (Reference 23), which were conducted to determine methane diffusion coefficients for various soils with differing particle size under varying conditions of moisture and pressures, that soils with a high percentage of clay can act as a gas barrier under favorable soil moisture conditions. However, the impermeable soil barrier method still remains relatively untested. Some synthetic membranes have been utilized in landfill construction, but these have been used primarily for the purpose of controlling the flow of leachates.

The literature contains very little reference to pre-construction gas control systems constructed in conjunction with sanitary landfills. It is probable, however, that much of the work in this area is still in progress and has not been publicized or reported. One example of such a system (Reference 24) is a sanitary landfill located in Kansas City, Kansas, which was initiated by the Mid-American Regional Council, Kansas City, Missouri. The project is supported in part by a demonstration grant from the Office of Solid Waste Management Programs, U.S. Environmental Protection Agency. The completed site is to be utilized for a regional park, which will include several public buildings and recreational facilities. Several homes are also located adjacent to the landfill site. Recognizing the potential dangers to these structures from landfill generated combustible gas, a combination permeable and impermeable system for gas venting is being constructed as part of the landfill. A soil blanket under the fill, laid primarily to control downward flow of leachates, also will provide a relatively impermeable barrier to the downward movement of gases. To allow ventilation of gases from the fill, a portion of the one-foot thick daily soil cover of each lift of the fill at the site perimeter is being removed to allow gases to pass readily upward through each lift. A trench two to three feet deep will be excavated and backfilled with gravel at the top of the fill in the final earth cover around the site edge. A permeable channel is thereby provided through which landfill gases can travel readily and vent to the atmosphere. The effectiveness of this method of gas control has not been established.

More common pre-construction systems are those that are designed and constructed for protection of structures which are erected on or adjacent to a completed landfill. Numerous examples of these gas control systems are in existence, although reported cases in the literature are rather limited (Reference 25) and include examples of techniques used to protect various structures such as school buildings, a market building and a residential area. In most cases the control systems involve vent pipes around the perimeter of the structure or within the building itself, gravel trenches, impermeable barriers around the foundations and under the floor slabs, or a combination of these.

Observations of some recent gas barrier installations in southern California were obtained from interviews with designers, developers and public agency personnel. Information from these interviews is presented below.

For protection of a public market located on natural ground adjacent to a landfill, a series of trenches were excavated in the subgrade under the building and backfilled with gravel. The trenches were spaced approximately 12 to 15 feet on center and were 12 inches deep and 12 inches wide. These trenches extend the full width of the building, terminating at the foundation walls. Two-inch diameter vertical vent pipes were placed in the walls of the building and connected to each gravel trench at the perimeter of the building. As an additional precaution, the entire subgrade beneath the floor slab was covered with a protective impermeable 10-mil polyethylene membrane which was laid on a two-inch sand bed. Venting of the trenches and subgrade area occurs by natural ventilation only, and no provisions were made for forced ventilation. Periodic measurements of gas concentrations have not detected the presence of combustible gas within the confines of the building, indicating that the precautions taken are satisfactorily venting the combustible gases from beneath the building.

At the site of a new apartment building complex located adjacent to an old 70 to 130 feet deep landfill which was formerly a diatomaceous earth mine, a gas interceptor trench was employed as a means to channel landfill generated gases away from the building complex. The trench extends the full width of the development and was installed in natural material between the fill and the buildings. The trench is approximately 18 feet deep and 24 inches wide, and is filled with gravel. To vent the trench, which will eventually be sealed over with pavement, four-inch diameter pipes were installed vertically at intervals of 30 to 40 feet.

The public agency that constructed this fill also utilized a similar gravel filled cut-off trench in a different location to intercept the gases that might flow from the fill to adjacent private property and home sites. In this case, the trench was 30 inches wide, 20 feet deep and 1,050 feet long. This trench was left open to the atmosphere for venting purposes and has successfully arrested all gas migration to the endangered properties. Recent measurements of gas concentrations on both sides of the venting trench indicate that the trench is still acting as a satisfactory deterrent to migration of the gases.

A more sophisticated gas control system will be used for a public service building complex to be constructed adjacent to a former landfill where monitoring has indicated the presence of combustible gas. The entire construction area is being filled with earth cover for a depth of approximately 50 feet to bring the level of the completed surface to that of the adjacent developments. Prior to filling, a trench was excavated in the original ground in which a six-inch diameter perforated gas collector pipe was placed. The trench is seven feet deep and two feet wide and is backfilled with gravel and sealed at the top with a plastic membrane. The total control system extends for a distance of approximately 850 feet and consists of two separate segments. The first segment, which is 450 feet long, consists of a gravel trench, perforated pipe and four vertical gravel-filled wells, which extend upward from the trench to the surface of the new fill. A four-inch diameter perforated vent pipe was installed in each 24-inch diameter vertical well and connected to the perforated collector pipe. These pipes extend 10 feet above the finished surface. Each extended vent pipe, which is nonperforated, is capped with a gas burn-off device. The second segment, which extends for approximately 400 feet, consists of the gravel trench, six-inch diameter perforated collector pipe and five 24-inch diameter gravel-filled wells. These wells are approximately 50 feet deep and contain a four-inch diameter perforated pipe connected to a six-inch diameter collector pipe. This segment contains only one four-inch diameter vent pipe which is connected to the collector pipe and extends upward through the new fill, terminating 10 feet above the finished surface. In the middle of the control system, each collector pipe is connected to a six-inch diameter nonperforated riser pipe, which extends vertically to the surface and is capped. If needed these two pipes can be utilized for forced ventilation of gases by installing a vacuum pump on the system. A series of gas monitoring probes are also being installed as part of this system for measurement of gas concentration at various depths and for continual monitoring and evaluation of the system.

Other examples, which are mostly of similar design (but for which little definitive information is available), exist and consist of gravel-filled wells, gravel-filled trenches or both. Some control systems employ forced ventilation in conjunction with gravel-filled wells and trenches, whereas others rely entirely upon natural ventilation. The permeable method for gas control appears to be more commonly employed because such systems are known to have performed satisfactorily and are relatively inexpensive and simple to install.

Examples of pre-construction systems utilized elsewhere in the nation are few. One of these systems is located near Boston, Massachusetts at the site of the new University of Massachusetts Columbia Point Campus in Boston Harbor (Reference 26). The seven-building University complex is being constructed on a completed dump site where substantial quantities of methane gas and some hydrogen sulfide have been detected. To assure safe beneficial occupancy of the buildings after completion, an elaborate gas detection and control system has been designed and installed for each building at this site. Each system consists of a network of perforated pipes laid in a gravel blanket beneath the floor of the building. The perforated pipes are connected to collector pipes which convey the gases to a vertical venting system existing above roof level. The gravel blanket is overlain with an impermeable gas barrier (40-mil polyvinyl chloride membrane) placed over a concrete mudsill, and all subterranean utility entries to the building are sealed. Each piping network is of varying size, predicated upon quantities of gas flow and head losses in the system. Automatic gas analyzers and control panels in each system provide continual printout readings of combustible gas concentrations beneath the buildings and from occupiable interior spaces. The control panels activate the gas-evacuation pumps and air-inlet valves when combustible gas concentrations reach a pre-set level. All such systems will be monitored at a central console and may be separately monitored and controlled. One building at a lower grade is protected with a membrane-enclosed rock blanket filled with nitrogen under pressure, and a sub-ramp space is constantly purged by means of a blower and pipe network. Performance checks of the University of Massachusetts systems are underway, and all systems appear to be performing satisfactorily.

Post-Construction Systems

As mentioned previously, the majority of the gas control systems reported in the literature are of the post-construction type and have been constructed to eliminate an existing and potentially dangerous condition. Many of these systems have been experimental in nature and are the forerunners of many of the pre-construction systems discussed above.

Three experimental post-construction gas control systems have been developed and tested in Los Angeles County as part of a three-year research study (Reference 3).

The system that has been most extensively tested and evaluated consists of five wells which are spaced 40 feet apart and are constructed in natural ground adjacent to the landfill interface. Each well is 30 inches in diameter and 60 feet deep. The wells are divided into three separate levels. A six-inch diameter perforated pipe is installed to the bottom of each level of the gravel-filled well. Each level is topped with a layer of concrete to eliminate short-circuiting within the well during pumping from various levels. The three perforated pipes from each well are connected to an eight-inch diameter header pipe that is connected to a 25-horsepower exhaust blower.

An extensive testing and monitoring program was conducted to examine the relative effectiveness of this gas control system in reducing or preventing gas migration beyond the vertical plane of the well system to the adjacent properties. The basic conclusions drawn from the program were that natural ventilation of the wells did not provide an effective barrier to gas migration; that some forced ventilation across the plane of the wells is necessary to arrest gas migration; and that with continuous pumping at the rate of 80 scfm per well, well spacings of 150 to 200 feet may be sufficient for the control of migrating gases. It should be noted, however, that these conclusions are for the particular test installation described and reported upon, and may not be exactly applicable to other areas with different soil and other environmental conditions.

An extensive post-construction system has been employed by the City of Los Angeles for controlling the migration of gases from an active landfill into an adjacent residential area and a school building complex (Reference 27). Several test systems were constructed and evaluated prior to installation of the principal permanent system. The basic permanent system consists of 17 ventilation wells 25 feet deep, spaced on 150-foot centers with a design withdrawal rate of 200 scfm from each well. It had been determined from earlier test programs conducted on three of these wells that the spacing of the wells, and thus the zone of influence of each well, was a function of the withdrawal rate from each well, and that the depth of the well was not a significant factor in the overall effectiveness of the control system. These criteria were used in designing the main system. The City chose a 25-foot depth, which was considered to be sufficient. The wells were placed along two sides of the 125 to 150 feet deep fill only (opposite the residential area on one side and the school area on the other side). The other two sides of the former gravel pit had previously been lined with a clay barrier, placed as the fill progressed, to prevent water intrusion from adjacent spreading grounds. It was expected that the clay liner would also serve as a gas barrier, and therefore no forced ventilation system was installed on those two sides. In recent (1974) observations, it is apparent that gas is migrating beneath the wells. Installation of additional wells, 100 feet deep, is planned.

The wells in the above system are two feet in diameter and are drilled in natural ground. A six-inch diameter perforated polyvinyl chloride pipe was placed in each well, and the wells were backfilled with gravel. Each well pipe is connected to a vitrified clay header pipe that runs three-fourths of a mile to a 15-horsepower blower. The blower feeds an induced draft vapor fume incinerator that uses natural gas as a supplementary fuel. To date, tests have indicated that gas migration has been controlled by this ventilation system and that odors can be controlled by the fume combustion chamber. However, further tests are being conducted to determine optimum flow rates, effective areas of influence of each well, the total amount of gas produced and the rate of gas production with respect to time.

A system similar to that being used by the City of Los Angeles (as described above) was utilized by the County Sanitation Districts of Los Angeles County to control the movement of gases from the completed portion of one of their active sanitary landfills. The fill is adjoined on one side by residences and a church. In order to assure that gases would not migrate to these areas, a series of 18 24-inch wells, varying in depth from 30 to 40 feet and spaced 100 feet apart, have been drilled to date (1974). A six-inch diameter polyvinyl chloride perforated pipe was placed in each well, after which the wells were backfilled with gravel to within eight feet of the surface. Each well was capped with a layer of driller's mud and three feet of concrete, and was then backfilled with earth to the finished surface. Each well pipe was connected to a header pipe, which was connected to a 5-horsepower suction blower. Two locally-fabricated burners, each receiving 400- to 625-scfm gas flow, are installed on piping assemblies from the blower exhaust and operated in parallel. Although gas flow is less than the design value, preliminary results indicate that gas movement into the adjacent properties are being arrested by this control system. It became necessary, however, to install seven additional wells to the original 11-well system. The burners, equipped with automatic pilot lights, operate continuously.

A gas control system utilizing natural ventilation was installed by a manufacturing company to protect its building complex. The system was installed approximately 150 feet from the edge of an old landfill in conjunction with the construction of an addition to an existing building and extended the full length of the complex bordering upon an old landfill site. The installation consists of a series of gravel-filled wells spaced 20 feet on centers and a gravel-filled trench five feet in depth. Each well is two feet in diameter and 40 feet in depth. A four-inch diameter perforated pipe was placed in the trench to collect the gases from the wells and the trench area. Vertical risers, four inches in diameter and connected to the trench pipe at a spacing of approximately 100 feet, extend up the wall of the building for emission of gases above the top of the buildings. The effectiveness of this control system is presently unknown.

CHAPTER VI

SELECTION, DESIGN AND INSTALLATION OF PROTOTYPE GAS BARRIER

HISTORY OF SITE DEVELOPMENT

Development of the Link Road landfill, the Armory and other facilities on or near the landfill is described in Chapter II. Primary features of interest with regard to design and installation of the gas barrier included an estimate of the gas production potential of the landfill's contents, the permeability of the adjacent soils, the history of combustible gas concentrations and migration, the proximity to the landfill of buildings and facilities to be protected and the location of underground facilities.

In 1973, the Link Road landfill was 24 years old, the last refuse having been placed near the Armory in September 1969. Extensive settlement had occurred just back of the Armory and the fire training area. Settlement was continuing, the landfill surface was covered with weeds and landfill-generated gases were venting from the soil cover through extensive cracks in a number of areas.

In July 1973, over 100,000 cubic yards, or approximately 162,000 tons, of new soil cover were placed over the old cover throughout most of the undeveloped upper portions of the landfill to restore final grade and to fill settlement areas. This represents an additional load on the upper surface of the landfill of over 500 pounds per square foot. Depth of new cover placement back of the Armory was three to four feet.

SITE DESCRIPTION

Physical Features

Topography--

The landfill occupies approximately 40 acres of a 60-acre tract in the southeast portion of Winston-Salem. The perimeter of the landfill extends about 5,600 feet.

Originally, the site consisted of a relatively steep hillside in the vicinity of the present Armory, with a ravine running easterly along the present line of the 72-inch storm drain. A small stream ran through this area and in the flat portion of the site, near Salem Creek, the stream bed contained fairly extensive swampy areas. The terrain slopes generally southeast from the highest elevations near the eastern boundary of the landfill site towards Salem Creek, which is about 70 feet lower. Final topography and typical cross-sections are shown in Figures 3 and 4. As landfilling progressed, wastes were initially deposited in the areas near Salem Creek. Drainage ditches were used to dewater the flat areas and work progressed up slope, finally terminating near original grade in the vicinity of the Armory. During operation of the abattoir, highly organic slaughterhouse wastes and dead animals were buried nearby. A small amount of refuse was also compacted over a limited section of the incinerator residue area and covered prior to conversion of this area into a parking and maintenance area.

The present fire training area is grassed and relatively flat, sloping gently to the center of the main landfilled area. Some settlement areas still exist in which water stands. Surface cracks are evident. The peripheral road drains through a storm-sewer system to the 72-inch main storm drain. Most of the parking and maintenance area is surfaced with a 12- to 18-inch thick well-packed layer of crushed stone. A small portion is paved with asphalt, and street drains divert runoff to the main storm drain. The entry road and the immediate area around the Armory are paved with asphalt and drain to the main storm drain. Relatively shallow sanitary sewers cross the parking area from Forsyth Technical Institute and connect with sewers entering the property from Silas Creek Parkway and passing southeastward by the Armory. Sewers and drains from the Armory connect to this sewer. A looped eight-inch water main passes through the parking area to serve the hydrants in the fire training area.

The upper surface of the completed landfill is relatively flat, but beyond the fire training area and to the east of the Armory, it begins sloping rapidly towards Salem Creek. Surface drainage is to the southeast, and no severe surface drainage problems have been noted.

Soils--

The soils at the base of the landfill are primarily sandy, with a relatively low clay content. Soil information obtained during preliminary testing for foundation design in the vicinity of the Armory indicated a rather sandy soil, with unsuitable bearing capacity for building construction in some areas. The cover material obtained on site was generally of a sandy nature with relatively low clay content. Varying amounts of soil cover material were brought in from time to time from a number of sources during the development of the landfill, and there is no consistent pattern of soil cover by type.

Climate--

The Winston-Salem area has a relatively moderate climate characteristic of inland areas of the Piedmont. Average annual precipitation is about 42 inches with a major amount of precipitation occurring in the early summer and early winter months. Temperatures in summer rarely exceed the mid-90's. Winter weather is generally moderate with snow and subfreezing weather of relatively light intensity and duration.

Hydrology--

Boring logs of subsurface explorations, placement of probes and excavation for the prototype gas barrier indicated that the groundwater table is between 25 and 30 feet below the surface along the line of the barrier, i.e., outside the landfill at the higher elevations. Similar exploration in the landfill, however, indicated water levels within three to five feet of the surface toward the center of the fill. These findings indicate occurrence of saturated areas throughout the landfill due either to water penetrating the soil cover or emanating from subterranean springs, with most occurrences in settlement areas. It is apparent that most of the mass of the landfill has reached field saturation, a condition conducive to maximum gas production.

Deposited Refuse--

Field checks indicated that wastes buried in the landfill had an average density of about 26 pounds per cubic foot. The average depth of fill was considered, for design purposes, to be 35 feet. As reported by Winston-Salem officials, the refuse to cover ratio was 2 to 1.

Other Features--

The principal areas of concern with regard to gas migration and potential hazards at the Link Road site are along the boundaries between the landfill and its most elevated periphery. Here the major construction of facilities has taken place, and the facilities are in the upgrade zone of gas migration. In the fire training area, deposition of highly organic wastes and lack of compaction may be resulting in high gas generation and migration toward the parking area and the Armory. Gas was not found above the periphery road in early investigations, however.

The placement of roads, buildings, crushed stone, sidewalks and paved parking and access areas in the general vicinity of the Armory has reduced vertical venting of gases from underlying refuse and has directed migration of gases toward the Armory. The surface seal afforded by the paving and crushed stone will, however, serve a useful function in the operation of the gas barrier since short-circuiting of air through the soil into the active barrier system will be reduced.

COMBUSTIBLE GAS CONCENTRATIONS AT LINK ROAD DISPOSAL SITE

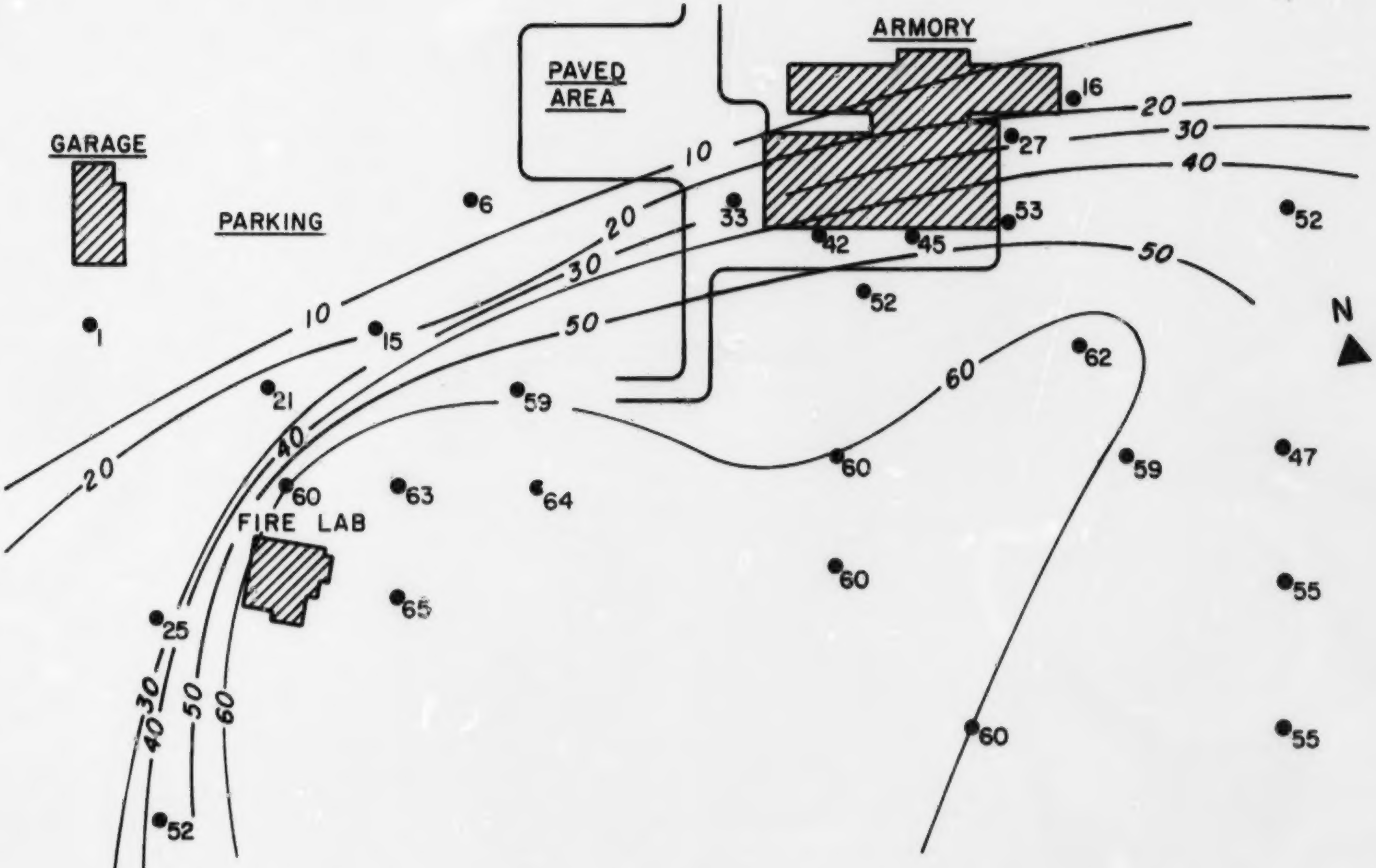
Areal Distribution

The concentration of explosive gases in soil voids within and adjacent to the landfill area is a positive indication of sources of gas generation and general direction of long-term movement. Because of the wide fluctuations observed in gas concentrations from day to day, average annual gas concentrations from the deep (25 feet) sampling probes were used to obtain the combustible gas concentration contour map shown on Figure 6. High concentrations were observed throughout the landfill, with relatively abrupt declines at the peripheries. Near the Armory gas concentrations persist for a considerable distance from the landfill edge, which is an indication of the relative ease of gas passage through the media lying between the fill and the building. Gas contour gradients between the fill and the truck parking area and the garage are somewhat larger, indicating lower gas permeability in the soils. Relatively high concentrations persist at the outermost probe at the landfill edge nearest the abattoir.

The observation of a relatively gentle gas concentration gradient, i.e., low resistance to flow, in the direction of the Armory in 1973 is coupled with the observation of a soil-air relative-pressure gradient in the same direction. Manometers connected to pressure probes installed in the peripheral area of the landfill in a line extending toward the Armory (Figure 15) consistently recorded decreasing pressures in the direction of the building over a one-month period of measurements in early 1974, as shown in Figure 7. Gauge pressure readings within the landfill reached as high as 200-mm water column, whereas those nearest the building vascillated near zero. Thus, the pressure and the concentration gradients along this particular direction induced both mass flow and the diffusion of combustible gas toward the building prior to the construction of the barrier.

Temporal Variations

Monitoring of combustible gas concentrations from a large number of probes in the Armory was conducted during the period 1970 to early 1974. The large quantity of data obtained were plotted, generalized and a number of representative or critical stations were selected for presentation in Figure 8.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CONTOUR INTERVAL: 10 PERCENT CH_4 BY VOLUME

Figure 6: Combustible gas concentration distribution in Link Road disposal site, 1973

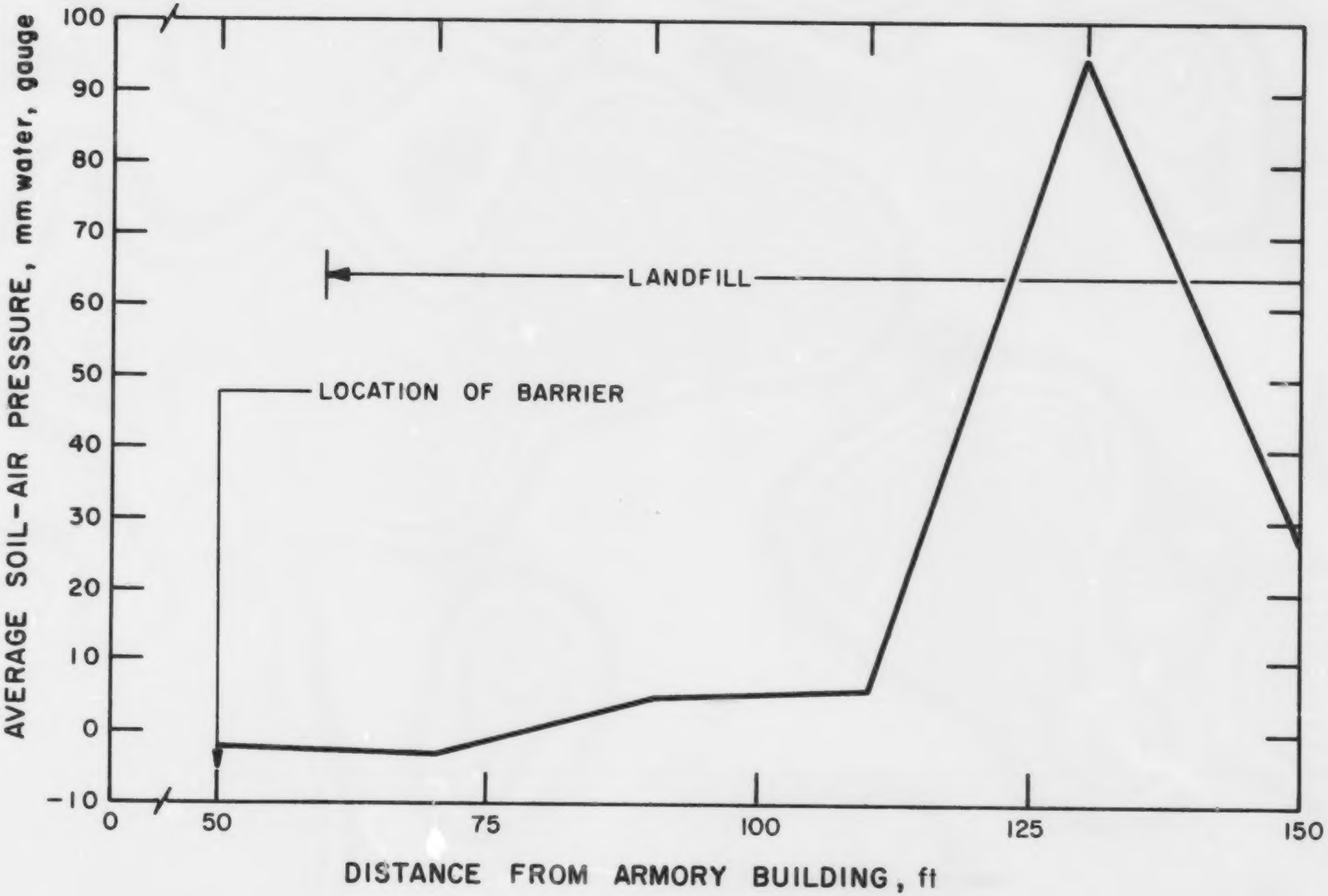


Figure 7: Soil-air pressure gradient toward Armory prior to barrier operation

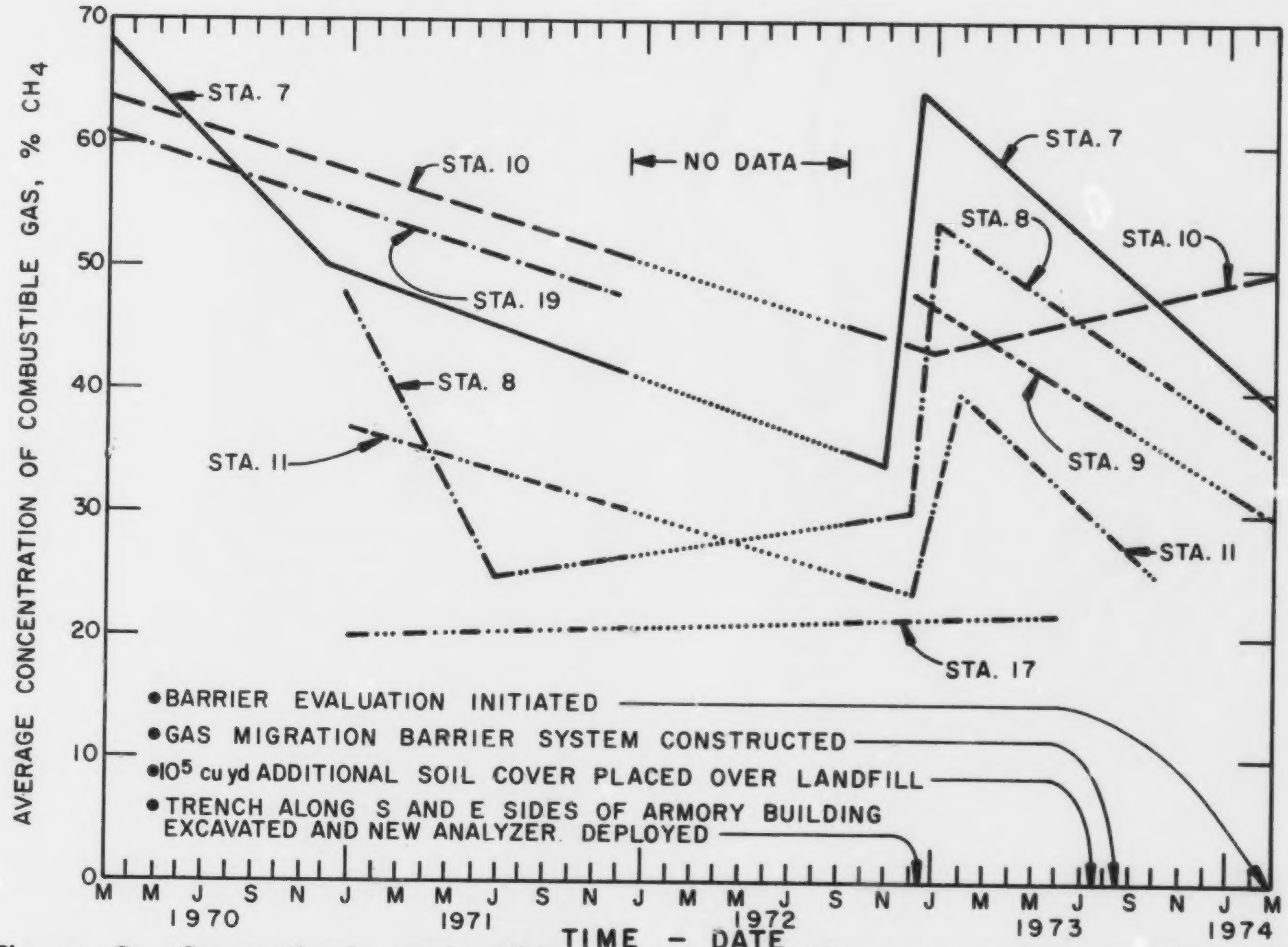


Figure 8: Generalized combustible gas concentrations at several stations near Armory

Rigorous attempts at correlating combustible gas concentrations with rainfall and temperature variations failed to demonstrate any regular patterns. However, it can be observed from Figure 8 that a steady decline of combustible gas concentration had been occurring over the period of monitoring, before barrier construction, at all stations in the vicinity of the Armory (Stations 7, 8, 9, 10 and 11, Figure 5).

The sudden rise in concentration of explosive gases noted in late 1972 coincides with the excavation of an L-shaped trench along the south and east sides of the Armory. It is believed that backfilling of this trench with loose material caused migrating combustible gas from areas of higher concentrations to move more readily toward the probe stations than was possible previously. At about the same time that the trench was dug, a new gas analyzer was purchased and deployed by the monitoring personnel. It was a few months later that the new gas analyzer was found to be reading five to 10 percentage points higher than the previously-used analyzer. The combination of these two events tend to explain the sudden rise in gas concentrations that occurred in late 1972. Soon after the sudden rise, a gradual decline was observed with a rate somewhat higher than that observed in the early part of the monitoring period.

Altogether, trends shown in Figures 6, 7 and 8 confirm the specific conclusions reached earlier about gradual gas concentration reductions over time, the response of the concentration at a given peripheral point to permeability of media between that point and the landfill, and the existence of an overwhelming mass flow component in the migration of gases away from the landfill.

EVALUATION OF ALTERNATIVE GAS BARRIER SYSTEMS

Three alternative gas barrier systems were evaluated for the purpose of selecting a suitable method of gas control for the Link Road disposal site. The alternatives considered were forced ventilation, natural ventilation and impervious membrane. Three modes of operation of the forced ventilation method were considered: high-flow (∿100 scfm/well) ventilation, low-flow (∿10 scfm/well) ventilation combined with the use of a surface seal and low-flow ($\sim$10 scfm/well) ventilation without the use of surface seal.

The objectives and functions of high-flow, forced-ventilation and low-flow, forced-ventilation systems are quite different. The objective of the high-flow, forced-ventilation system is to create a relatively large bulk flow of soil-air gases, which includes a substantial amount of overlying atmospheric air that is pulled through the surface of the landfill, from the area of influence of each well. Therefore, in addition to providing an effective barrier against migration of landfill-generated gases, this system effects a dilution of combustible gases in the soil-air on the landfill side in the vicinity of the barrier. Therefore, in this sytem, no attempt is made to exclude atmospheric air, except in the immediate vicinity of each well. The objective of the low-flow, forced-ventilation system is to create a vertical plane, or barrier, of ubiquitous negative pressure between wells which will intercept landfill-generated gases naturally migrating toward the barrier and cause them to flow to a well due to the induced negative pressure gradient. In this system, a minimum amount of landfill-generated gases, i.e., only that necessary to create the barrier of negative pressure, is extracted from the area of influence of each well. To be effective, this system requires that the inflow of overlying atmospheric air into the landfill in the vicinity of the barrier be kept to an absolute minimum.

As described in Chapter V, the state-of-the-art of gas control technology is by and large experimental at this point in time. The experimental and demonstration projects involving gas migration barriers have generally failed to provide universal design criteria. However, existing systems of gas migration control have demonstrated the feasibility of controlling the flow of gases from landfills. Furthermore, the limited experience has provided some field data on the mode of operation and effectiveness of several gas ventilation methods. These data are of value for developing new design criteria for conditions other than those for which direct experience is available.

Several criteria were considered in evaluating the various methods of gas migration control. The methods considered were ranked under each criterion and given an appropriate score in accordance with the quantitative or subjective information presently available. The judgement on the final ranking of the systems may be more readily justifiable in some cases than in others where performance data are scarce or inapplicable. Nevertheless, it is believed that a fair and impartial evaluation of each system was obtained with the scoring system used.

Cost

Total annual costs were obtained from estimates of capital cost and operation and maintenance cost for each alternative, and are shown in Table 1. All capital costs were amortized over a 10-year period at an interest rate of six percent. As indicated in Table 1, the highest rank or score of five was assigned to the system with the least total annual cost and a score of one to the most expensive. Detailed information on capital cost requirements for forced ventilation systems, natural ventilation systems and impermeable barrier systems is presented in Appendix A.

Table 1. ESTIMATED COSTS OF ALTERNATIVE GAS BARRIER SYSTEMS
(dollars)

Alternative system	Total capital cost	Annual O&M cost	Total annual cost	Rank/ Score
Forced ventilation				
a. High flow	52,000	3,000	10,000	2
b. Low flow with seal	73,600	1,200	11,500	1
c. Low flow without seal	37,600	850	6,100	3
Natural ventilation	10,000	0	1,400	5
Impermeable barrier	24,500	500	4,000	4

Effectiveness

Because effectiveness is the primary factor of concern in the selection of a gas control system, this parameter was assigned a weight of three. Thus in a one-to-five relative ranking of the alternatives (with the highest rank assigned to the most effective method), the score for effectiveness of an alternative system would range from three to 15. Experience with existing systems indicates that forced-ventilation systems, as a group, are far more effective than either the natural ventilation or the impermeable barrier systems. Natural ventilation systems have generally been least effective in preventing gas migration from a disposal site. Because high-flow, forced-ventilation barrier systems have proven to be effective, this alternative was assigned the highest score.

Low-flow, forced-ventilation barrier systems have not been tested to date as a means of preventing gas migration. Therefore, their relative ranking is based upon theoretical fluid flow behavior which clearly indicates that the low-flow, forced-ventilation system would be far more effective than natural ventilation or impermeable barrier methods. By the same token, it is surmised that the effectiveness of low-flow, forced-ventilation methods may be somewhat lower than high-flow, forced-ventilation systems. Theoretical considerations also imply that the use of a surface seal, as discussed in the sections below, would increase the effectiveness of low-flow, forced-ventilation systems in intercepting migrating gas.

The assigned rank and score of alternative systems from the viewpoint of effectiveness is presented in Table 2.

Maintainability

Maintainability is important because it bears directly upon the reliability of and continuous safety provided by a given barrier system. Generally, the simpler the system the more maintainable it will be. Conversely, the more complicated and larger the barrier appurtenances, the greater are chances for breakdown and the need for maintenance. Therefore, the natural ventilation and the impermeable barriers would be more maintainable than those requiring pipelines, pumps and control structures.

Table 2. RELATIVE EFFECTIVENESS OF ALTERNATIVE GAS BARRIER SYSTEMS

Alternative system	Rank	Score
Forced ventilation		
a. High flow	5	15
b. Low flow with seal	4	12
c. Low flow without seal	3	9
Natural ventilation	1	3
Impermeable barrier	2	6

The rank and score for the five alternative systems with respect to maintainability is presented in Table 3.

Table 3. RELATIVE MAINTAINABILITY OF ALTERNATIVE GAS BARRIER SYSTEMS

Alternative systems	Possible maintenance problems	Rank/ Score
Forced ventilation		
a. High flow	Pump failure, control mechanisms maintenance, short-circuiting of air flow	1
b. Low flow with seal	Pump failure, control mechanisms, seal breakage	2
c. Low flow without seal	Pump failure, control mechanisms, short-circuiting	3
Natural ventilation	Plugging of porous material by surface drainage	4
Impermeable barrier	Seal breakage	5

Controllability

This criterion is a measure of the ability of operators to adjust the operation of a system in accordance with the feedback provided by the monitoring system. Thus, in a highly controllable system, working with 100 percent effectiveness, operating costs can be lowered by reducing flow rates or decreasing pumpage periods, or both. The energy input to the same system may be increased to intercept any gases upon the inception or increase in gas migration. The rank and score of the five alternative systems with respect to controllability is shown in Table 4.

Table 4. RELATIVE CONTROLLABILITY OF ALTERNATIVE GAS BARRIER SYSTEMS

Alternative system	Control feature	Rank/Score
Forced ventilation		
a. High flow	Flow rate (decreasable), well spacing	3
b. Low flow with seal	Flow rate (wide range of variation), well spacing, strip width	5
c. Low flow without seal	Flow rate (wide range of variation), well spacing	4
Natural ventilation	None	1
Impermeable barrier	None	1

Environmental Effects

The most noticeable environmental effects of disposal site gas migration barrier systems are noise, odor, options for final use of the site and the aesthetic appearance of system appurtenances. Noise and odor are primarily caused by the forced-ventilation systems involving use of motors and the discharge of pumped refuse gases into the atmosphere from a concentrated point source. The high-flow, forced-ventilation systems, by nature, pose the greatest noise level and the highest discharges of malodorous gases. The low-flow, forced-ventilation systems, on the other hand, are relatively quiet and contribute much smaller volumes of landfill gases to the surrounding areas. The existence or absence of surface seal does not appear to contribute significantly and in a direct manner to change in either noise level or odor dispersal. Indirectly, however, it may reduce total pumpage flow requirement, which would lower noise and rates of malodorous gas extraction. Both natural ventilation and impermeable barrier systems are completely noise free. The natural ventilation systems conceivably can contribute more maladorous gases along the barrier by providing freer venting access than can the impermeable barrier system.

From the point of view of options for final use of the disposal site, the forced-ventilation systems are favored over the others due to the fact that such systems would more readily enable beneficial uses of areas on and adjacent to the completed disposal sites due to their greater effectiveness. Such uses include public parks and recreation sites and other facilities which may be developed upon the completed fill areas.

Aesthetically, the impermeable barrier system is completely innocuous after construction is completed, whereas the natural ventilation system will have some protruding vent pipes. The forced-ventilation systems, on the other hand, pose structural unsightliness in proportion to the magnitude of pumpage and surface sealing. To the extent that these features detract from the natural open-space setting, the forced ventilation systems would be aesthetically more objectionable. The rating scores given each alternative barrier system with respect to environmental effects are presented in Table 5.

Disturbance Due to Construction

In the course of constructing new gas migration barrier systems, a certain amount of earth excavation, well drilling, pipeline installation and other activities are certain to disturb the site for the duration of construction work. Placement of either a natural ventilation system or an impermeable membrane will require a large amount of excavation and backfilling work with the attendant stockpiling of fill material as well as disposal of excavated soil. These disruptions are monumental relative to well drilling and surface seal application required in the forced-ventilation systems. The assigned scores for disruption due to construction of the alternative systems are presented in Table 6.

Table 5. RELATIVE ENVIRONMENTAL IMPACT OF ALTERNATIVE GAS BARRIER SYSTEMS

Alternative system	Rank/Score			
	Noise	Odor	Final use options	Aesthetics
Forced ventilation				
a. High flow	1	1	3	2
b. Low flow with seal	3	3	5	2
c. Low flow without seal	2	2	4	3
Natural ventilation	5	4	2	4
Impermeable barrier	5	5	1	5

Table 6. RELATIVE DISRUPTION DURING CONSTRUCTION OF ALTERNATIVE GAS BARRIER SYSTEMS

Alternative system	Rank/Score
Forced ventilation	
a. High flow	5
b. Low flow with seal	4
c. Low flow without seal	5
Natural ventilation	1
Impermeable barrier	1

Experimentation and Innovation

Because of the paucity of information presently available on the entire problem of gas migration control, it is deemed important to emphasize innovation and experimentation in this field. Furthermore, a system with built-in flexibility, allowing variation of the independent parameters (pumpage rate, strip width, etc.), is considered to be a great advantage. The advantages are twofold. First it allows the system to be "tuned" to the particular peculiarities of the site, and secondly it provides data for use in design and operation of similar gas migration barriers at other locations. The innovative character of each system and its flexibility are judged on the basis of past experience or lack thereof with the respective systems. The impermeable barrier system is one of the oldest concepts, followed closely by the natural ventilation alternative. On the contrary, application of a surface seal and a low-flow, forced-ventilation barrier is the most novel concept in gas migration control. High-flow, forced-ventilation systems have been in use in several locations for some time and are thus ranked intermediate among the other alternative systems insofar as experimentation and innovation are concerned. The ranking and scoring of the alternative systems from this respect are summarized in Table 7.

Table 7. RELATIVE NOVELTY OF ALTERNATIVE GAS BARRIER SYSTEMS

Alternative system	Novelty feature	Rank/Score
Forced ventilation		
a. High flow	None	3
b. Low flow with seal	Low flow, surface seal	5
c. Low flow without seal	Low flow	4
Natural ventilation	None	2
Impermeable barrier	None	1

SELECTION OF THE GAS BARRIER SYSTEM

A summary of the scores assigned each alternative gas control system is presented in Table 8. The low-flow, forced-ventilation system with a surface seal received the highest cumulative score, followed by the low-flow system without the surface seal. The high-flow, forced-ventilation system has the next highest score, followed by the impermeable barrier system. The natural ventilation system has the lowest total score.

On the basis of these scores, the low-flow, forced-ventilation system with surface seal was selected for design to provide a barrier against migrating gases from the Link Road landfill.

THEORETICAL CONSIDERATIONS

Laminar flow of fluids through porous media is governed by Darcy's law. In order to be able to use analytic tools to describe the movement of landfill gases toward outlying areas, it is necessary to make certain justifiable simplifying assumptions concerning the fluids (air-methane mixture), the porous media (refuse, fill and undisturbed soils adjacent to the landfill) and the flow process. These assumptions and the justifications therefor are given, in some length, before a presentation of the theoretical considerations for the design of a low-flow, forced-ventilation system with surface seal.

Assumptions

Laminar Flow--

Darcy's law has been experimentally found valid for all flows in the laminar range, i.e., with Reynold's numbers below unity. Because the kinematic visocity of air is about 10 times greater than that of water, the law allows an air flow 10 times that of water within the applicability of Darcy's law. Therefore, inasmuch as Darcy's law is universally used successfully to describe groundwater movement under most conditions, laminar flow should prevail for all gas movement problems encountered in barrier system design and related analyses.

Table 8. SUMMARY OF RELATIVE SCORES FOR ALTERNATIVE GAS BARRIER SYSTEMS

Alternative systems	Total annual cost	Effectiveness	Maintainability	Controllability	Con struction disturbance	Environmental effects	Experimentation & innovation	Total score
Forced ventilation								
a. High flow	2	15	1	3	5	7	3	36
b. Low flow with seal	1	12	2	5	4	13	5	42
c. Low flow without seal	3	9	3	4	5	11	4	39
Natural ventilation	5	3	4	1	1	15	2	31
Impermeable barrier	4	6	5	1	1	16	1	34

Isotropic Media--

Mechanics of fluid flow in porous media almost universally assume isotropicity of the medium. Flows occurring in a well-type barrier system are in fact three-dimensional, even though the principal direction of movement of gas is perpendicular to the barrier. The only anisotropicity of significance may be due to the various horizons developed during the soil-forming process. As long as flow along the vertical dimension is minimal and differentiation of soil horizons is not highly exaggerated, the assumption of isotropicity is not expected to limit the applicability of Darcy's law to flow situations under consideration. Generally, the effects of anisotropic media upon flow conditions are only of theoretical significance. In practical applications these effects are subordinated by the scale of the flow parameters.

Homogeneous Media--

The assumption of homogeneity of soils along and in the vicinity of the gas migration barrier led to the use of a single representative permeability factor for the entire length of the gas barrier. The superficial fallacy of this assumption is evident in the range of permeabilities measured for the air-dried samples taken from various points in the vicinity of the barrier. Soil permeability variations are so common within relatively short distances that unless a great number of samples are obtained, it is not safe to assign the results of one test to the zone of influence of a number of wells. Thus a single representative permeability value was judiciously selected for use in the design of the entire barrier system. Natural soil variations will generally be averaged out for the entire system, as well as for each well, resulting in flows close to theoretical derivations. The problem of lack of homogeneity is similarly handled in groundwater flow analyses successfully.

Steady-State Flow--

At the beginning of the operation of the gas migration barrier system, a transient flow condition will exist with complex flow and pressure distribution patterns in the vicinity of the barrier. This time-variant condition will last until streamlines and the pressure distribution network finally become stabilized in a steady-state pattern closely resembling those predicted by the equations. During periods of wetting and drying of the soil surfaces (such as at the onset of the wet and the dry seasons) nonsteady-state gas flow will prevail due to changing soil permeability in those periods. A long-term decrease in gas generation rate in the disposal area will impose an additional transitory character to the gas flow parameters.

The effects that the nonsteady character of flow are liable to exert upon flow conditions are all such that design based upon a steady-state assumption is biased toward providing a conservative system.

Constant Gas Density--

In the range of negative pressures produced by the pumping equipment proposed for the barrier system (less than 0.01 atm), gas densities should not vary by more than one percent. Small variations will not affect the accuracy of predicted flows to a significant or measurable degree.

Analytical Relationships

For the condition under consideration, namely the presence of a lower confinement to gaseous flow in the form of the groundwater table which is relatively impermeable compared to the overlying unsaturated soil and an upper confinement in the form of paving or other appropriate seal, the flow of gas toward any well in the barrier is given by the Thiem equation for radial flow of fluids in a confined aquifer (an adaptation of Darcy's law); *viz.*,

$$q = \frac{-2 \pi h k \Delta p}{\mu \ln (r_e/r_w)} \qquad (1)$$

where:

q = flow to each well (cfs)

h = depth to groundwater table (ft)

k = intrinsic soil permeability (ft^2)

Δp = imposed pressure differential between well and limit of influence, r_e (psf)

μ = average gas viscosity ($lb\text{-}sec/ft^2$)

r_e/r_w = ratio of radius of influence of well to radius of well

In order to intercept all gases moving toward the protected area, wells should be spaced along the barrier so that pumpage from all wells in the barrier equals gas movement toward the barrier. Flow from each side of the barrier may be calculated by using Darcy's equation directly, i.e.,

$$Q = \frac{-k}{\mu} (h\ L) \frac{\Delta P}{\Delta X} \tag{2}$$

where:
Q = total gas flow from each side to the gas barrier (cfs)
L = length of barrier (ft)
ΔP = average pressure differential between the barrier and an orthogonal distance ΔX away (psf)
ΔX = distance over which ΔP acts (ft)

Accurate estimation of the pressure gradient, $\Delta P/\Delta X$, is the key to the usefulness of Equation 2. Because the negative pressure along the barrier, indicated by Δp, will vary from a maxima at the wells to a minima at midpoints between the wells, the effective negative pressure at the barrier is assumed to be about 0.5 Δp. Therefore,

$$\Delta P = 0.5\ \Delta p \tag{3}$$

The total system flow is equal to 2Q and the number of wells along the barrier, n, may be determined by dividing the total flow from both sides of the barrier by pumpage rate from each well; *viz.*,

$$n = \frac{2\ Q}{q} \tag{4}$$

Spacing between wells, S, is obtained by dividing the length of the barrier system by the number of required wells; i.e.,

$$S = \frac{L}{n} \tag{5}$$

Spacing between wells can also be determined independently of most system variables by substituting Equations 1, 2, 3 and 4 into Equation 5; *viz.*,

$$S = \frac{2\pi\ \Delta X}{\ln\ (r_e/r_w)} \tag{6}$$

To assure confined aquifer conditions, the width of seal along the barrier, W, must be only sufficient to provide the pressure gradient $\Delta P/\Delta X$. Therefore,

$$W = 2\ \Delta X \tag{7}$$

Cost Minimization

The economic trade offs between the width of the sealed barrier and the number of wells along the barrier can be evaluated using the relation:

$$C = C_0 + C_1 + C_2 \tag{8}$$

where:
C = total cost of the barrier
C_0 = costs independent of number of wells and spacing
C_1 = costs associated with the number of wells in the system = $K_1\ n$
K_1 = cost of each well and appurtenances thereto
C_2 = costs associated with the sealed strip = $2\ K_2\ L\ \Delta X$
K_2 = cost of paving a unit width along the entire length of the strip

A minimum total cost solution can be obtained if C is related to ΔX by substituting Equations 1, 2, 3 and 4 into Equation 8; i.e.,

$$C = C_0 + \frac{L\ \ln\ (r_e/r_w)\ K_1}{2\ \pi\ \Delta X} + 2\ K_2\ L\ \Delta X \tag{9}$$

Differentiating C with respect to ΔX gives:

$$\frac{dC}{d(\Delta X)} = - \frac{L\ \ln\ (r_e/r_w)\ K_1}{2\ \pi\ (\Delta X)^2} + 2\ K_2\ L$$

Setting $\frac{dC}{d(\Delta X)}$ equal to zero to obtain the minimum cost solution gives:

$$\Delta X = \sqrt{\ln\ (r_e/r_w)/4\pi} \cdot \sqrt{K_1/K_2} \tag{10}$$

The first multiplicand is a physical constant for a given system and the second can be determined from prevailing unit costs of the various elements of the barrier system.

GAS BARRIER DESIGN

Width of Surface Seal

The most economical ΔX is determined from Equation 10. For a well radius, r_w, of one foot and an assumed radius of influence, r_e, of 100 feet:

$$\Delta X = \sqrt{\ln (100/1)/4\pi} \cdot \sqrt{K_1/K_2}$$

$$= 0.605\sqrt{K_1/K_2} \qquad (11)$$

Choice of an appropriate numerical value for r_e depends, to a certain extent, upon the expected final value of the width, W, of the sealed strip along the barrier. The width of seal will determine the approximate radius of influence of the well by imposing a lower limit of ΔX feet upon the path that the air stream will traverse horizontally before arriving at the intake perforations of the wells. This assignment, arbitrary as it may appear, is not too critical in the solution of Equation 10, because of the logarithmic and square root function in which r_e appears. (A 50 or 100 percent error in estimation of r_e will result in only a 4.6 or 8.4 percent error, respectively, in the value of ΔX.)

The unit cost of wells, K_1, is comprised of the costs of drilling, piping, gravel placement and monitoring and control devices for each well. These costs, under the existing conditions, and for a 30-feet well depth are:

Drilling @ \$20/ft		=	\$600/well
Piping @ 3/ft		=	90/well
Gravel @ 2/ft		=	60/well
Monitoring (orifice meter)		=	350/well
Control (butterfly valve)		=	150/well
TOTAL	K_1	=	\$1,250/well

The unit cost of sealing the barrier strip, K_2, is the unit cost of placing sealant on each square foot of the barrier. Cost of sealant is estimated to be $\$0.18/ft^2$.

Replacing K_1 and K_2 in Equation 11 gives:

$$\Delta X = 0.605 \sqrt{1,250/0.18} = 50 \text{ ft}$$

This value of ΔX is then used as a basis for the computation of flow toward wells, spacing of wells and actual strip width.

The resulting width of the paved strip along the line of well is:

$$W = 2 \Delta X = 100 \text{ ft}$$

Flow Rate and Capacity

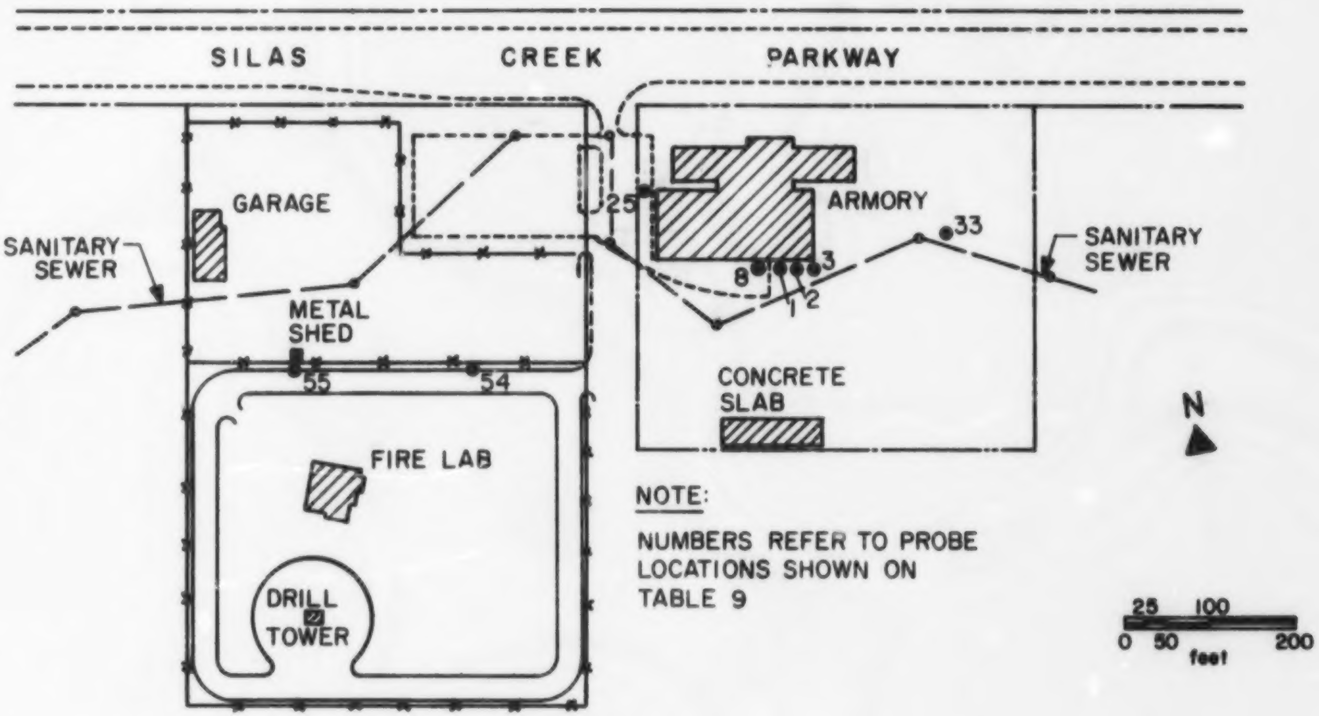
An important parameter in the computation of flow toward the barrier and into the wells is soil permeability, k. Thirteen soil samples from eight different locations along the proposed barrier and at two depths in five locations were analyzed in the laboratory. A nonsteady-state air permeability test (Reference 28) was utilized to determine the permeability of the air-dried and uniformly repacked soil samples. The results are presented in Table 9, and locations of samples are shown in Figure 9. Evidently, soils in the vicinity of the Link Road disposal site are highly permeable. For the purposes of this particular development, the deeper strata are of greater significance because the perforations in the pipes will be placed at these depths and not near the surface. Therefore, the average value of intrinsic permeabilities, *viz.*, 69.9×10^{-12} ft^2 observed along the barrier at the deeper (14 to 19 feet) levels, was selected for use in Equations 1 and 2. The depth to groundwater along the barrier varies between 25 to 30 feet, so that the 14 to 19 feet deep samples should be the most representative of average conditions throughout the depth of soil along the barrier and in the region of well perforations. Selection of the permeability parameter is a rather critical function requiring familiarity with the laboratory test procedures on the disturbed samples as well as an appreciation of the vagaries of sample site selection. The selection of the uniformly-applied permeability value was influenced in part by the particle-size distribution analysis performed on the samples which yielded the permeability values reported in Table 9. The particle-size distribution data for these soil samples are also shown in Table 9.

Table 9. PARTICLE-SIZE DISTRIBUTION AND PERMEABILITY OF SOILS IN VICINITY OF PROPOSED BARRIER

Probe[a]	Location[a]	Sample depth, ft	Sieve analysis of soils, percentage passing sieve				Permeability, 10^{-12} ft^2
			No. 4 4760μ	No. 10 2000μ	No. 40 417μ	No. 200 74μ	
1	Southwest of Armory supply room[b]	6	86.5	59.5	21.7	5.3	425
2	South of Armory supply room[b]	5	100.0	100.0	62.4	15.9	37.8
3	Southeast of Armory supply room[b]	6	99.3	94.2	54.6	9.8	160
8	South of Armory building[c]	4 to 6	98.4	95.6	63.1	22.5	126
		14 to 16	99.4	97.8	68.8	28.6	61.2
25	West of Armory building[c]	4 to 6	99.6	95.8	6[illegible].8	19.5	33.4
		14 to 16	97.1	88.6	60.6	18.5	43.2
33	East of Armory building[c]	4 to 6	98.7	95.2	73.2	37.4	95.5
		14 to 16	99.4	97.5	69.0	35.1	110
54	South of truck park area[c]	4 to 6	97.0	93.0	69.2	33.1	76.5
		14 to 16	97.9	93.6	68.9	35.4	54.0
55	South of metal shed[c]	4 to 6	85.3	76.9	53.7	24.3	2.16
		17 to 19	98.4	95.1	80.6	35.0	81.0

---

[a] Figure 9 shows location of probes in the waste disposal site and vicinity.
[b] Samples were collected from the bottom of a trench dug along the southern wall of the supply room.
[c] Core samples were obtained from the given depths using standard sampling techniques (Reference 28).


SILAS CREEK PARKWAY
GARAGE
SANITARY SEWER
METAL SHED
55
54
FIRE LAB
DRILL TOWER
25
ARMORY
8
1
2
3
33
SANITARY SEWER
CONCRETE SLAB
N
25
100
0
50
200
feet

NOTE:
NUMBERS REFER TO PROBE LOCATIONS SHOWN ON TABLE 9

Figure 9: Soil permeability samples and associated probe locations in vicinity of proposed barrier

The choice of a viscosity value for gases flowing in the vicinity of the proposed barrier was made with full cognizance of pressure and temperature influences, as well as methane concentration, upon the gas mixture. The pressure dependence of the gas-mixture viscosity, in the pressure ranges encountered, is negligible. The value chosen for viscosity of the gas mixture allows for the most conservative computation of flows in the temperature and methane concentration ranges expected to be experienced under various operating circumstances.

Gas viscosity decreases with decreasing temperature and with increasing methane concentration. The lowest probable soil-air temperature is about 10°C at the depths where gas flow under forced ventilation will occur. The estimated methane concentration of the gas being generated in the landfill is expected to be about 29 percent in 1973, the time that the barrier system will become operational (see Figure 11). Linear interpolation of reported values for viscosity of air and of methane at standard temperatures results in a design value for the methane-air mixture of 157 micropoises.

Using Equation 1 to calculate flow toward each well, and using the following data:

h = 30 ft, as measured in the field from ground surface to the groundwater table along the proposed barrier

$k = 69.9 \times 10^{-12}$ ft^2, selected representative intrinsic permeability based upon laboratory tests

Δp = 0.01 atmosphere (21.2 psf), selected vacuum to be imposed by pump

μ = 157 micropoises ($3.28\ 10^{-7}$ lb-sec/ft^2)

r_e = 100 ft, assumed radius of influence of a well

r_w = 1 ft, a design parameter

the flow to each well will be:

$$q = \frac{2\,\pi\ (30)(6.99\cdot 10^{-11})(21.2)}{3.28\cdot 10^{-7}(4.61)} = 0.185 \text{ cfs} = 11.1 \text{ cfm}$$

Using Equation 2 to compute the total flow from each orthogonal direction toward the gas migration barrier, and the additional appropriate data:

L = 1,000 ft, the length of the main legs of the barrier
$\Delta P = 0.5\Delta p = 0.005$ atm (10.6 psf)
ΔX = 50 ft, as determined from cost analysis

the total flow from one side of the barrier will be:

$$Q = \frac{-6.99\cdot 10^{-11}(30)(1{,}000)(-10.6)}{3.28\cdot 10^{-7}(50)} = 1.36 \text{ cfs} = 81.3 \text{ cfm}$$

Flow toward the barrier from both directions will be:

$$2\,Q = 163 \text{ cfm}$$

Number of wells required is:

$$n = \frac{2\,Q}{q} = \frac{2(81.3)}{11.1} \approx 15 \text{ wells}$$

and required spacing between wells is:

$$S = \frac{L}{n} = \frac{1{,}000}{15} = 67 \text{ ft}$$

It should be noted that the flow, given above, is for the main east-west legs of the gas barrier. The short north-south leg on the west side of the Armory includes three wells with 3(11.1) = 33.3 cfm total flow. Therefore:

Total system flow = 163 + 33 = 196 cfm

Estimated Gas Generation Rate

The state of knowledge about gas generation rates and quantities is relatively primitive. Some qualitative correlations between gas generation rate and climatic/hydrologic factors have been expressed indicating that warm and/or wet conditions promote larger overall biochemical degradation of the refuse and volumetric rates of gas generation.

It is logical to presume that combustible gas generation rate is in some direct fashion related to combustible gas concentration in the surrounding areas to the disposal site. Such a relation would exist whether gas transport were by diffusion or advection. Although combustible gas generation data are not available, combustible gas concentration values have been obtained at the Link Road disposal site over the past three years at several sampling locations. Individual sampling data were plotted and smoothed to eliminate the day-to-day variations in the concentration of the combustible gases. A plot of combustible gas concentrations for one typical sampling station is presented in Figure 10. To obtain a reasonable estimate of the pseudo-equilibrium gas generation rate suggested by Figure 10, a few logical assumptions are required regarding the quantitative nature of the events and conditions at the Link Road disposal site.

It has been reported (Reference 10) that a pound of refuse will ultimately produce 3.9 ft^3 of methane gas upon complete biochemical decomposition. For conservative design purposes, this value of refuse conversion to methane is assumed to apply at the Link Road disposal site.

The density of compacted refuse at the Link Road disposal site is estimated to average about 26 lb/ft^3.

The volume of the entire disposal site was estimated from cross-sectional profiles of the filled area determined by field surveys. A total volume of about 1.4×10^6 yd^3 has been filled with refuse and cover material. The refuse:cover ratio was estimated at 4:1 to be conservative in the design (the City has indicated a ratio of 2:1). The perimeter of the disposal site was measured at about 5,600 ft and the average fill depth was determined from actual borings to be about 35 ft.

A semi-logarithmic plot of combustible gas concentrations at Station 7 (see Figure 5 for location) versus time, which is shown in Figure 11, indicates the following relationship:

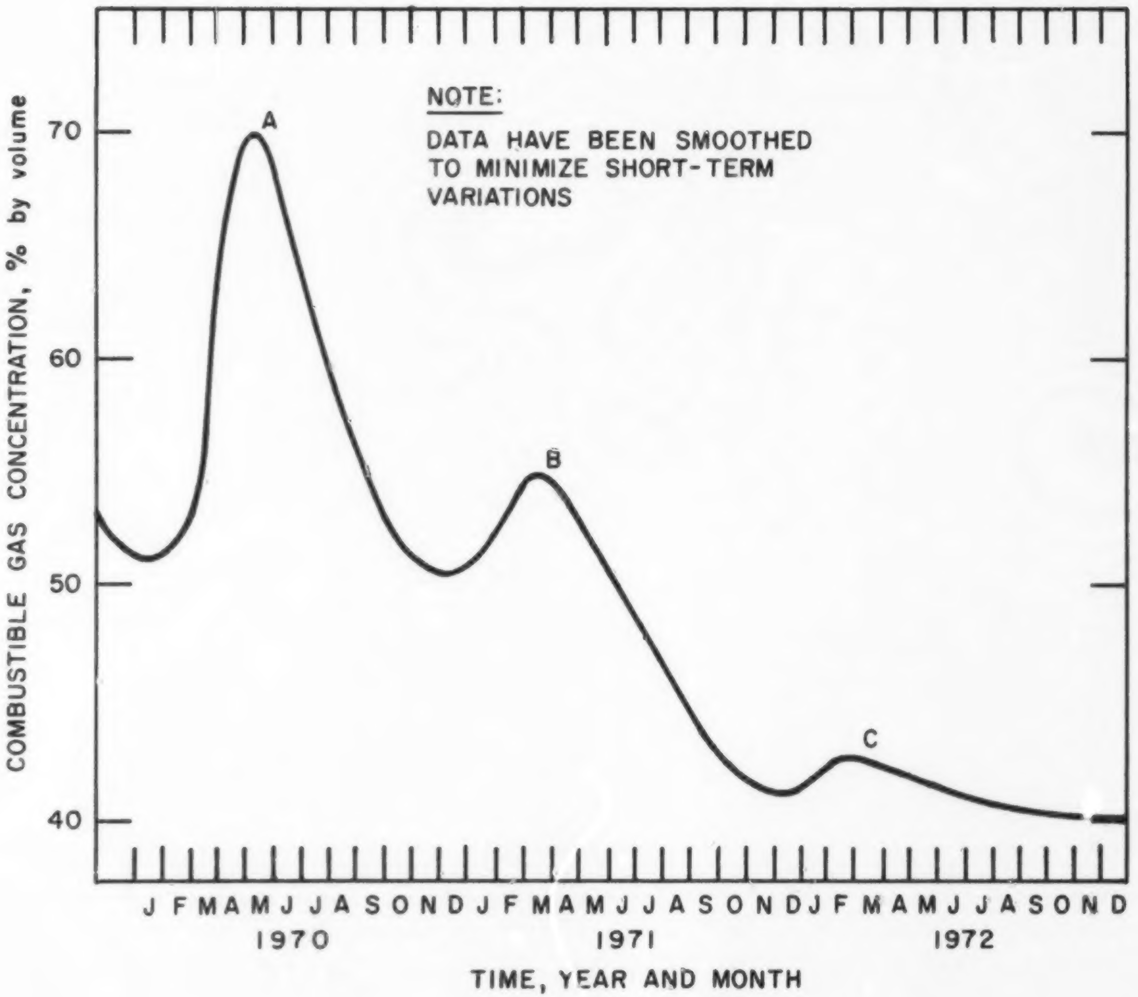


Figure 10: Historical variations of combustible gas concentration at station 7

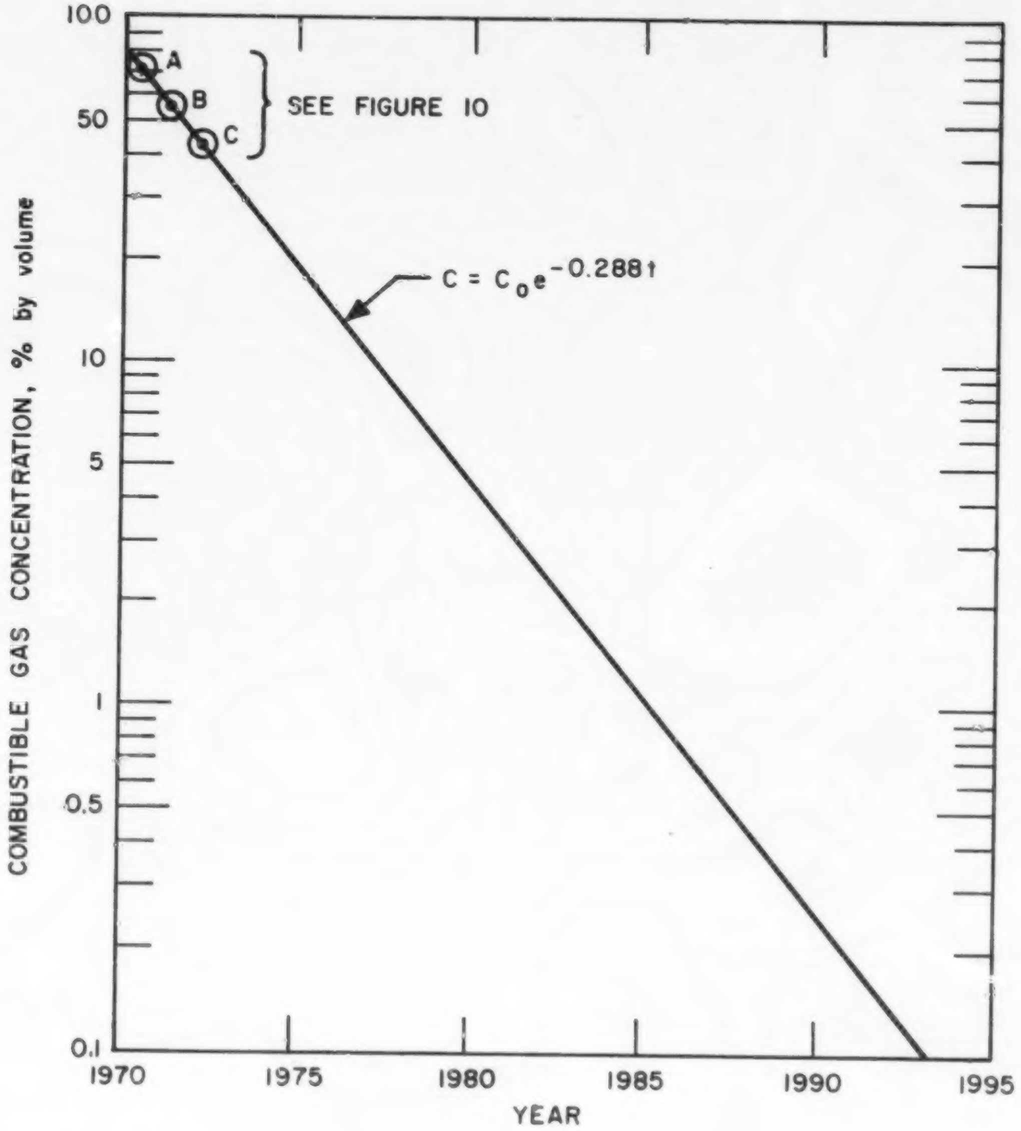


Figure II: Historical and projected concentration of combustible gas migrating from disposal area at station 7

$$C = C_0 \, e^{-0.288\ t} \tag{12}$$

where C_0 and C are combustible gas concentrations initially ($t = 0$) and at time, t, respectively. Figure 11 was based on only one sampling station because it provided the largest number of data and, of all sampling stations, it is located in the closest proximity of the Armory supply room where the flash fire occurred.

Assuming that gas generation rate is proportional to gas concentration at the periphery of the landfill during the decomposition period, Equation 12 can be rewritten for gas generation rates; *viz.*,

$$F = F_0 \, e^{-0.288\ t} \tag{13}$$

where F_0 and F are gas generation rates during the initial year and at some later year, t, after completion of the disposal operation. The value of F can be computed by integrating gas generation rate over the life of the landfill and equating it to total gas production expected from a pound of refuse; i.e.,

$$F\ dt = 3.9\ ft^3/lb \tag{14}$$

This procedure yields $F_0 = 1.082\ ft^3\ CH_4/lb$ in the initial year after disposal operations have been completed. Thus, Equation 13 becomes:

$$F = 1.082\ e^{-0.288\ t}$$

In mid-1973, when the barrier presumably will become operational, the annual gas generation will amount to $0.222\ ft^3\ CH_4/lb$.

On this basis, the average CH_4 flow rate during 1973 across a 1,000 feet long vertical cross-section of the landfill periphery will be:

$$\frac{4}{5} \times 1.4x10^6\ yd^3 \times 26\ \frac{lb}{ft^3} \times 27\ \frac{ft^3}{yd^3} \times 0.222\ \frac{ft^3}{lb\text{-}yr} \times 5.256 \times 10^5\ \frac{min}{yr}$$

$$\times \frac{1000}{5600} = 59.3\ cfm$$

The various simplifying assumptions made to arrive at this value are of such a nature as to make it a conservatively high estimate, particularly since no allowance was given to vertical venting through the surface of the disposal site, which may only be approached during periods when the disposal site surface is made nearly impermeable to upward gas movement due to precipitation, confining it to lateral migration. The 59 cfm maximum gas migration rate computed above is far below the design value of 163 cfm for the main branch (1,000 feet) of the low-flow, forced-ventilation system, which provides for a reasonable factor of safety.

Pipe Sizes

For a maximum allowable total dynamic head (friction) loss in the system of 10 inches of water column and a design total flow rate of 196 scfm, the suction header pipe should be four inches in diameter. A constant diameter suction header is provided throughout the system to simplify procurement and installation.

For the reasons discussed in the next section, the underground piping, consisting of the wells and suction header, was sized to accommodate a high-flow system, should it be required. In this case, for the same maximum allowable total dynamic head loss in the system of 10 inches of water column and a design total flow rate of about 1,800 scfm, the suction header pipe should be eight inches in diameter throughout. Because the flow in each short-section of well pipe will be relatively small and the concomitant head loss negligible, the well pipes were sized at four inches in diameter to allow for greater ease of perforation in the field.

CONSTRUCTION STRATEGY

Due to the relatively high estimated cost of the surface seal (about 45 percent of the total system cost) and the possibility that the existing surface may provide an adequate seal, a step-wise construction strategy was employed.

Because any of the three forced-ventilation systems are considered to be acceptable for controlling gas migration from the Link Road disposal site, the two low-flow, forced-ventilation systems can be designed to provide a backup capability by sizing the pipelines for maximum flows required in a high-flow, forced-ventilation system.

Preferred System: Low-Flow, Forced-Ventilation Without Surface Seal

Low-flow operation without surface seal was rated next-to-highest in total score in Table 8. However, because it is the least expensive of the forced-ventilation alternatives, it was chosen as the first system to be tested, and to be used if proven effective. Should the testing program indicate that satisfactory gas migration control is achieved with the low-flow system without a surface seal, no further construction--and additional expenses--would be necessary.

Contingency Plan I: Low-Flow, Forced-Ventilation With Surface Seal

If the low-flow system without a seal does not prove effective during the test period, a surface seal would be applied along the barrier, with width and other parameters specified in later sections. The provision of surface seal should assure gas migration control with the low flows predicated in the theoretical considerations.

Contingency Plan II: High-Flow, Forced-Ventilation

In the unlikely event that the testing program reveals gas migration beyond the barrier system while the low-flow, forced-ventilation system is in operation, flows can be increased by installation of much larger pumping capacity so that adequate protection is provided.

The initial design of the pipelines and pumpage facilities for the proposed barrier are carried out with the necessary provisions for conversion to high-flow pumpage rates of the magnitude already proved effective in other areas close to solid waste disposal sites. Thus, if the low flows prove not to be wholly effective (as judged by the testing program), pumpage rates can be increased without incurring excessive pipeline head losses.

CHAPTER VII

DESCRIPTION OF PROTOTYPE GAS BARRIER

PLANS AND SPECIFICATIONS

Detailed plans and specifications were prepared prior to construction of the gas barrier system. A brief description of the various components of the barrier system is presented herein in order to maintain adequate reference for the evaluation of the system performance, given in Chapter VIII.

The gas migration barrier is essentially a curtain of negative pressures, in relation to the atmosphere, maintained indefinitely by pumpage of gases from a series of wells along the curtain. Continuous maintenance of negative pressure at every point along the barrier--placed between the refuse disposal area and the Armory--is the key to provision of protection to the occupants. The line of wells, in relation to the landfill and the building, is presented in Figure 12.

BARRIER WELLS

Barrier wells, which provide the means for creation of negative relative pressure, are all similar to the one shown on Figure 13. The wells are all interconnected through an eight-inch diameter polyvinyl chloride header pipe, laid underground along the entire length of the barrier. A butterfly valve, installed between each well head and the header, controls flow from each well. This provision is important for balancing system flow and equalizing pressure drop along the barrier. Well heads are also equipped with quick-disconnect assemblies for field measurement of vacuum created in each well during operation. The valve

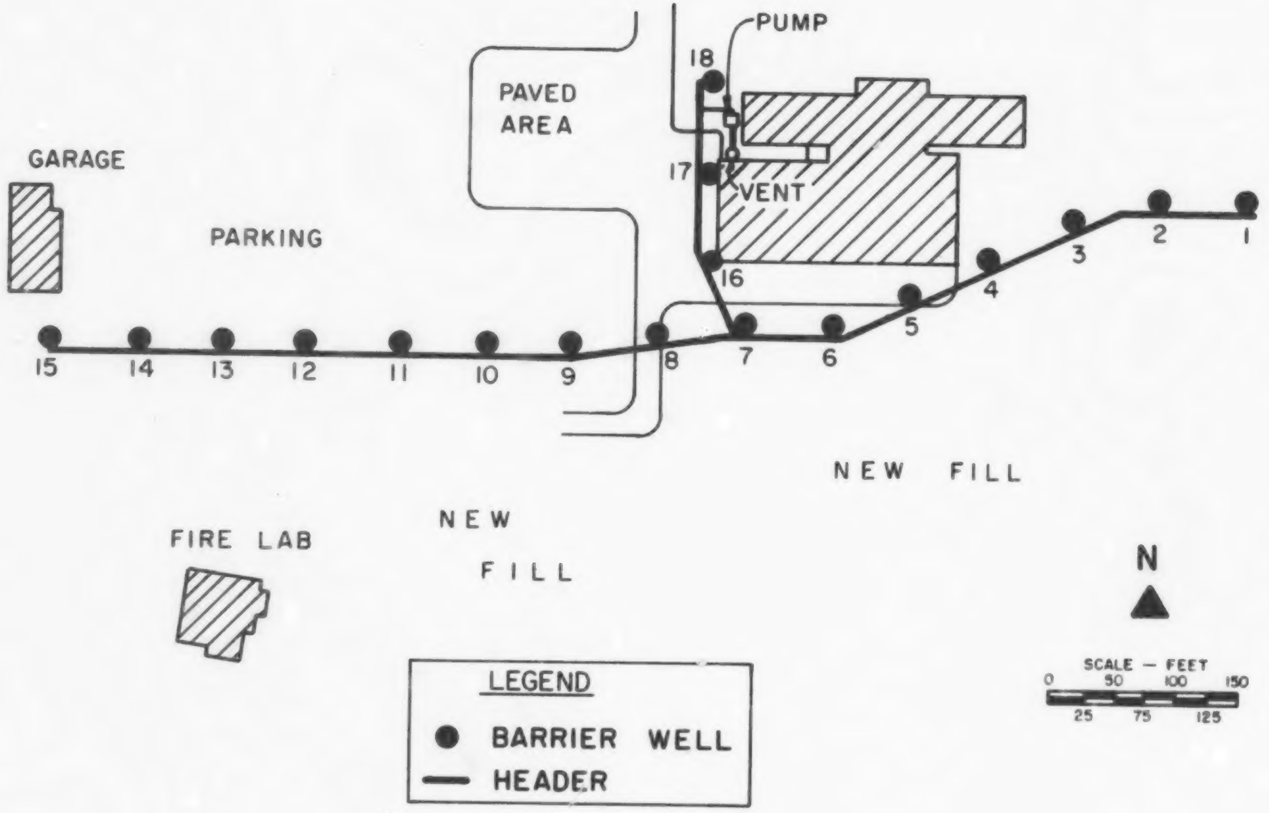

PUMP
18
PAVED
AREA
GARAGE
17
VENT
PARKING
16
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
NEW FILL
NEW
FILL
FIRE LAB
N
SCALE — FEET
0
50
100
150
25
75
125
LEGEND
BARRIER WELL
HEADER

Figure 12: Location of barrier wells, header, pump and vent

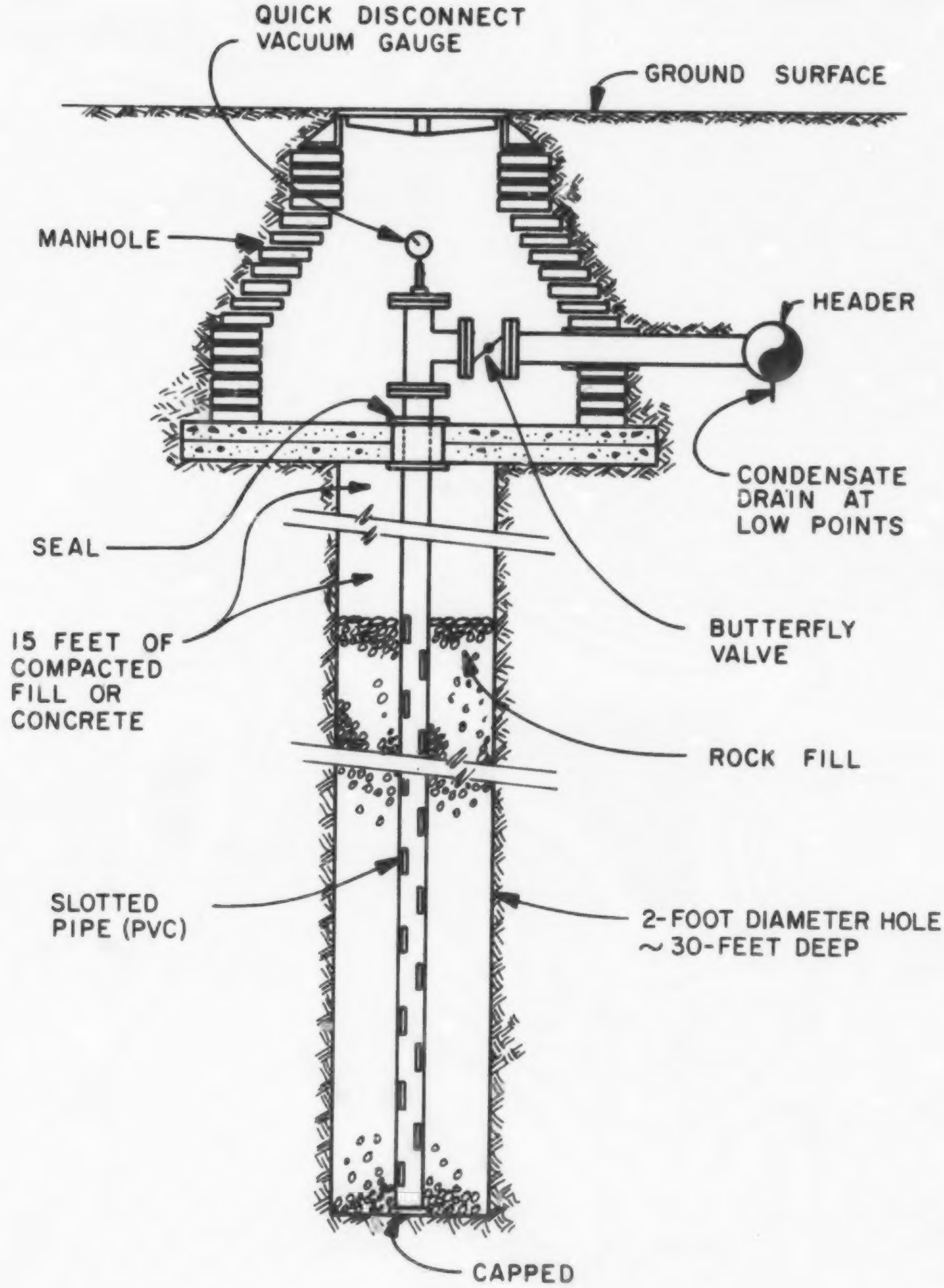

QUICK DISCONNECT VACUUM GAUGE
GROUND SURFACE
MANHOLE
HEADER
CONDENSATE DRAIN AT LOW POINTS
SEAL
15 FEET OF COMPACTED FILL OR CONCRETE
BUTTERFLY VALVE
ROCK FILL
SLOTTED PIPE (PVC)
2-FOOT DIAMETER HOLE ~ 30-FEET DEEP
CAPPED

Figure 13: Typical gas migration barrier well

and pressure gauge connection are located in accessible manholes. The wells consist of slotted four-inch diameter polyvinyl chloride pipes surrounded by coarse gravel. A 15-foot length of the unslotted section is immediately below the ground surface and at least 10 feet of the slotted section is above the groundwater table.

VACUUM PUMP

In order to produce a continuous relative negative pressure along the barrier, a positive-displacement, lobe-type vacuum pump, capable of pumping 250 scfm (the nearest available to design capacity of 196 scfm) of air-methane mixture at a vacuum of 10 inches of water column was provided. The pump was installed on the northwest corner of the Armory, and its suction pipe was connected to the northern leg of the barrier, as shown on Figure 12. A variable-speed drive system, consisting of a variable-type sheave, companion pulley and belt, was provided in order to afford a capability for testing system performance under different flow conditions.

GAS MONITORING AND SIGNALLING SYSTEM

The purpose of the monitoring and signalling system is twofold: (1) to provide the occupants of the National Guard Armory with an early warning of intrusion of refuse-generated combustible gas into the space between the Armory and the barrier and into the building and (2) to determine the long-term effectiveness of the gas migration barrier.

Because failure in a combustible gas barrier system could result in a threat to human life and property, it is imperative that the gas control system be provided with a fail-safe monitoring and signalling system designed to detect dangerous gas build-up in the building and to warn the occupants. Data obtained from the long-term monitoring program will supplement intensive test data which were obtained at the beginning of the operation of the barrier system. Valuable additional data, pertaining to the effectiveness of the selected system, can thus be acquired while at the same time ensuring the safety of the building's occupants.

Selected System Design Criteria and Characteristics

Components of the monitoring and signalling system must meet certain functional requirements to satisfy the system objectives. These components include the sampling network, the detection system and the signalling system.

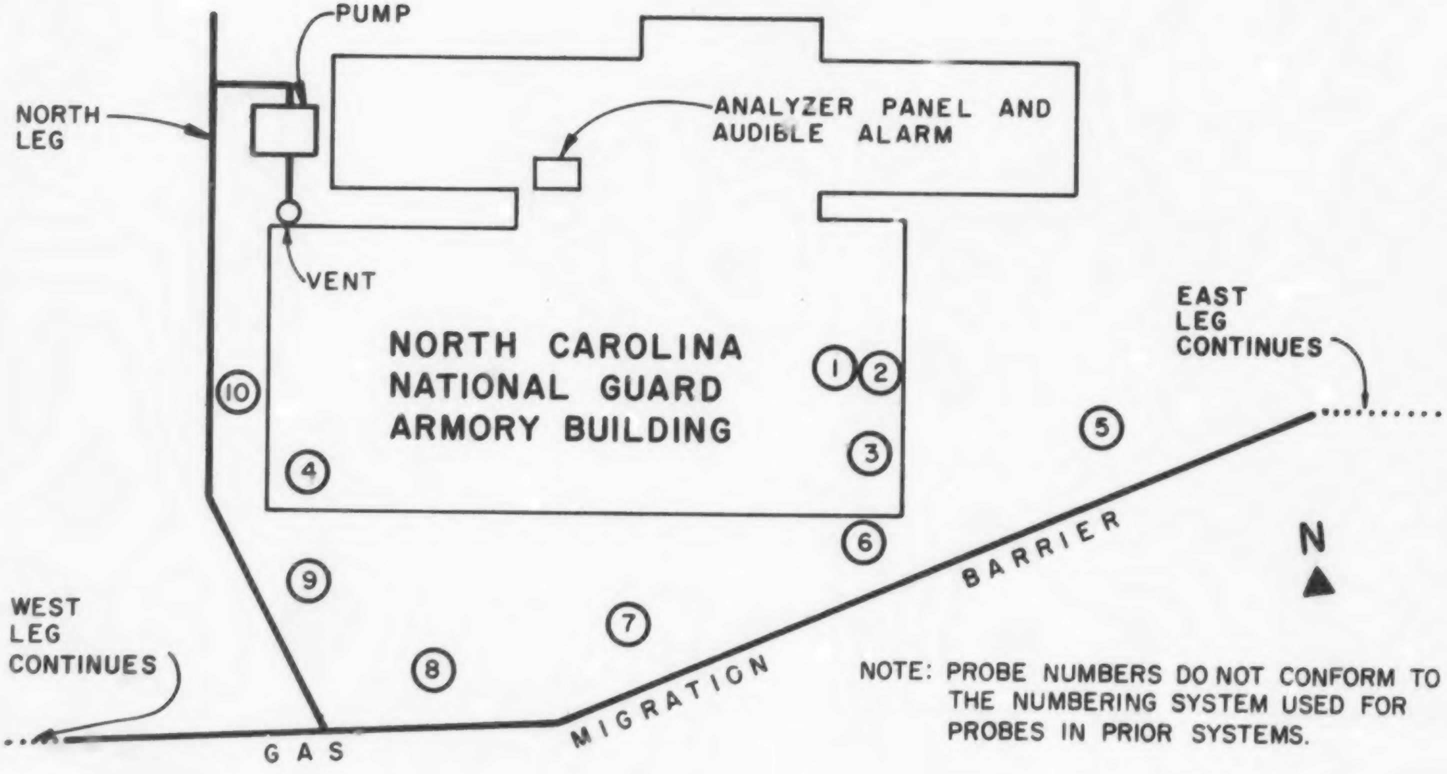
Sampling Network --

Sampling point locations were selected to ensure that gas will not accumulate unnoticed in the Armory. The network consists of probes located within the building and in the ground between the building and the gas migration barrier. Probes within the Armory provide a direct measurement of the parameter of concern, namely the presence of minute amounts of combustible gas in the Armory. Probes located in the ground between the Armory and the barrier provide a warning of the presence of gas passing the barrier toward the Armory. Such an event will allow implementation of remedial measures prior to detection of any explosive gas within the Armory.

Sampling points between the Armory and the gas migration barrier are located in such a manner as to intercept the most probable pathways for gas movement, namely midway between the gas extraction wells. The sampling points within the ground are located adequately remote from the Armory so that early warning of gas migration toward the Armory will allow remedial action, if deemed necessary. Gas samples are withdrawn at a depth which will provide an indication of maximum prevalent combustible gas concentrations.

Gas sampling points within the Armory are installed in locations where landfill gas might be expected to infiltrate or accumulate in the building. Possible danger points are deformation cracks in the below-grade structure of the building and unventilated high points in rooms or confined spaces.

The selected sampling network consists of four interior sampling points and six exterior sampling wells. Locations of sampling points are shown in Figure 14. Choice of locations of sample probes was based


PUMP
NORTH LEG
ANALYZER PANEL AND AUDIBLE ALARM
VENT
NORTH CAROLINA NATIONAL GUARD ARMORY BUILDING
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
EAST LEG CONTINUES
WEST LEG CONTINUES
GAS MIGRATION BARRIER
N

NOTE: PROBE NUMBERS DO NOT CONFORM TO THE NUMBERING SYSTEM USED FOR PROBES IN PRIOR SYSTEMS.

Figure 14: Sampling locations for detection and alarm system

on the results of the sampling program conducted during four years (1970 to 1974) and the predicted impact of the control measures on gas migration.

Interior gas sampling points are located near the ceiling in the supply room, vault, wool room and at the ground floor of the Police Academy in the southwest portion of the Armory. The exterior sampling wells will provide gas concentration data from 10 feet deep probes located approximately halfway between the gas control barrier and the Armory and spaced about midway between the gas extraction wells. This configuration and sampling depth will ensure best interception of the most probable pathways of gas migration, should any gases cross the barrier and provide adequate warning of increasing gas concentrations before hazardous levels are reached near any potential entry point.

Detection System--

The combustible gas analyzer selected for use in the gas monitoring system is relatively simple and robust and of a type common to mining and other gas detection applications. Extreme accuracy in analysis is of less importance than dependability of service. The selected system is designed to function reliably with minimal attendance, because technical staff is not expected to be available for frequent maintenance or testing of the equipment after the initial evaluation program.

Most of the available combustible gas detection devices have been developed for the mining industry. They consist of an electrically heated coil (sensor), the resistance of which varies in proportion to the heat of combustion generated by the burning of a gas mixture ignited by the coil, and a device for measuring the coil resistance. Where several locations are to be sampled and analyzed, it is both economical and convenient from the point of view of operation to centralize measurement and recording. In the selected system, samples are pumped from the various probe sources to a single sensor located at a central monitoring station.

The detection system, includes a MSA Model F gas analyzer, a 10-point recorder, sample pump and visual and audible alarms, mounted in a console located within the Armory (Figure 14). A continuously pumped sampling system with a centrally located gas sensor was considered preferential to individual sensors at every sampling well because pumping of the sample assures positive displacement of gas across the sensor. Each exterior sampling well is provided with an access point for combustible gas injection to test the function of the system, whereby known concentrations of test gas may be introduced into the well and monitored at the gas monitoring console.

Samples are withdrawn continuously from each interior and exterior sampling point and monitored sequentially in a step-wise manner. Gas from each interior sampling point is passed sequentially across the probe for a three-minute period; thus the interval between routine measurements of combustible gas from a particular point within the Armory is 12 minutes. This sequence is interrupted every two hours when gases withdrawn from the exterior sampling points are passed sequentially across the probe for a three-minute period. This lapse of time between exterior samplings is deemed adequate in light of the results of the evaluation program presented in Chapter VIII. Thus, monitoring of interior samples is interrupted for a period of 18 minutes while exterior samples are being measured. Analyzed gas samples and surplus by-pass gas are vented to the atmosphere above the roof of the Armory.

Measurements of percent of lower explosive limit of combustible gas are made and recorded on a 10-point recorder located in the monitoring console.

Signalling System--

The signalling system was designed to warn immediately all occupants of the Armory should explosive gas concentrations be approached within the confines of the building. An alarm, audible in all parts of the Armory, is provided, together with visual signals at the central monitoring station. In addition, visual signals are provided at the central measuring station if combustible gas is detected at any exterior sampling probe.

The detection system is also provided with audible and visual alarms to warn Armory occupants of electrical or mechanical failure of any of the system components.

The visual and audible alarms are activated at a pre-set combustible gas concentration of 25 percent of the lower explosive limit (LEL). This level is well within the analyzer's capability for accurate analysis and sufficiently below the LEL to allow necessary action long before the LEL is approached.

OPERATING PROCEDURES

Based upon preliminary results of the evaluation program, a set of operating procedures has been developed for use by field personnel during the active life of the landfill and the beneficial occupancy of the Armory. These procedures are divided into routine procedures, system tests and maintenance. It is crucial to the safety of the Armory premises that these procedures be followed regularly and precisely, and that any irregularities be promptly and properly corrected.

Routine Procedures

The pump is to be operated continuously at the lowest speed practicable (about 600 rpm) with the drive system provided. This speed of rotation should provide the necessary protection with minimal equipment wear. The regular operation of the system will, in the long term, result in breakdowns and failure of parts. Replacement parts and repair facilities must be readily available to minimize down time and prevent the possibility of gas movement into the vicinity of the Armory during these periods.

The recorder charts must be carefully reviewed by operating personnel at the time that they are changed. Any time that readings above zero percent lower explosive limit are obtained, time, date and concentration should be permanently recorded in a special book. This will allow ready reference and appropriate decision on the necessity for changing operational mode of the system. Although pressure readings need not be obtained as part of the routine procedures, it is important that access to and operation of the pressure probes (M1 through M10, Figure 15) be maintained and their destruction be avoided. Should future testing become necessary, existence of these probes will be of vital importance.

System Tests

Periodic tests of the integrity of the various system components are necessary to minimize repair and down time as well as to maximize reliability of the monitoring and signalling system. For major equipment, such as pump, motor, analyzer, recorder, etc., the instructions specified by the manufacturers should be followed carefully and strictly.

Once every six months, test gas with a known concentration of methane should be injected into the exterior sampling wells through the access points provided, while the system is placed on manual control for testing samples from a particular well. The volume of injected gas should be sufficient to fill the well casing and the volume immediately adjacent to it, or at least enough to effect a response at the monitoring panel. This quantity will be ascertained by field personnel through experience. Response of the analyzer to these tests should be noted in the special monitoring book kept near the analyzer panel.

After every shutdown (for repair, replacements, etc.), the record of the analyzer should be critically viewed for possible gas intrusion.

System Maintenance

All manufacturers' recommended maintenance procedures must be followed for pump, motor, analyzer, recorder and other equipment used for the Link Road landfill gas barrier system. Breakdowns and failures must be immediately attended and repaired.

SAFETY FEATURES

There are a number of safety features incorporated in the design, operational procedures and contingency provisions of the gas migration barrier system. The design of the barrier involves gas-well spacing and flow specification which together include provisions amounting to a very high factor of safety. While this margin may appear excessive, it should be noted that gas migration barrier design is still evolving and that human life may be jeopardized without provision of excess capability. The pump as well as the analyzer sampling units are designed to be explosion-proof, and excess combustible gases are vented to the atmosphere at a level above the roof of the Armory.

Operational procedures, described above, also include ample safety features which, if followed faithfully, should prevent any possibility of failure or danger to occupants.

Any mechanical system upon which safety of humans is based needs back-up contingency provisions. The gas barrier is no exception. Therefore, a series of back-up safety provisions are available for implementation upon indication of need. These provisions--none of which will probably ever be needed--are:

(1) If at any time the lowest speed of pump operation fails to intercept gas movement across the barrier, pump speed can be increased gradually until gas concentrations at the exterior probes (Probes 5 through 10, Figure 14) drop to zero.

(2) If provision (1) does not provide the necessary protection, all butterfly valves on Wells 9 through 15 (western leg of the barrier, shown on Figure 12) should be shut off. This action will almost double the flow from the wells immediately surrounding the building and should intercept any gas movement across the barrier.

(3) If both provisions (1) and (2) fail to provide protection, a surface seal (asbestos-cement, concrete, asphalt, bentonite, plastic sheeting, etc. as may be determined when and if the need arises) should be placed to a width of 100 feet along the barrier. This provision will prevent movement of atmospheric air along the barrier into the wells. The net effect will be the creation of a substantially greater vacuum midway between wells and hence a far greater assurance of interception of gases moving toward the building.

(4) Ultimately, if all the above provisions fail, the vacuum pump should be replaced with a larger pump with higher capacity. The wells and headers are sized such that the pumpage rates can be increased to as high as 10 to 20 times the rate which is expected to be satisfactory. Thus, there is no conceivable possibility that any provisions beyond this step need be implemented.

CHAPTER VIII

PERFORMANCE EVALUATION OF PROTOTYPE GAS BARRIER

INTRODUCTION

Protection of human life, property and the environment in and around the facilities near the Link Road waste disposal site has been the principal objective of constructing the gas migration barrier system. An indisputable assurance of its reliable and safe operation--over extended periods of time--is necessary before there can be safe occupancy and regular use of the buildings. A carefully planned, systematic and rigorous testing program has been conducted, and the results thoroughly examined and evaluated. These results were favorable, and indicate that, if the system continues to operate at the tested level, safe occupancy of the Armory permises can be anticipated in the relatively near future.

The primary objective of the testing and evaluation program was to aid in the selection of the most cost-effective mode of operation for the barrier system. The test sequence was planned to permit evaluation of each mode of operation independently and under similar conditions, insofar as prevailing constraints allowed. The program was designed to test and evaluate least-cost methods at the outset and to progress to more costly modes of operation only if the lower-cost methods failed to provide the necessary protection.

A secondary objective was to accumulate data and experience for better understanding of gas-flow phenomena near solid waste land disposal sites under the influence of the forced-ventilation gas barrier system.

The information will aid in designing other gas barrier systems in similar circumstances.

Measuring the zone of influence of individual wells and of the whole barrier under actual operating conditions was a key element in the program. This parameter helps determine the maximum well spacing which assures pressure reduction along barriers in future systems. Other parameters determined include noise levels at the pumps and flow distribution among the wells under different pumpage rates.

TEST EQUIPMENT AND INSTRUMENTATION

Some of the equipment used in the test program was similar to or identical with equipment installed for the continuous monitoring and signalling system. In addition, gas concentrations were determined using portable combustible gas analyzers. Soil-air pressures were determined from probes placed near the barrier. Atmospheric pressure was obtained from the meteorological station at the Greensboro, North Carolina, Airport approximately 35 miles from the Armory.

Flow Meter

A cumulative flow meter was installed on the discharge manifold of the vacuum pump. Cumulative flow over a known period of time was read and recorded, including the date and time at which readings were obtained.

Gas Probes

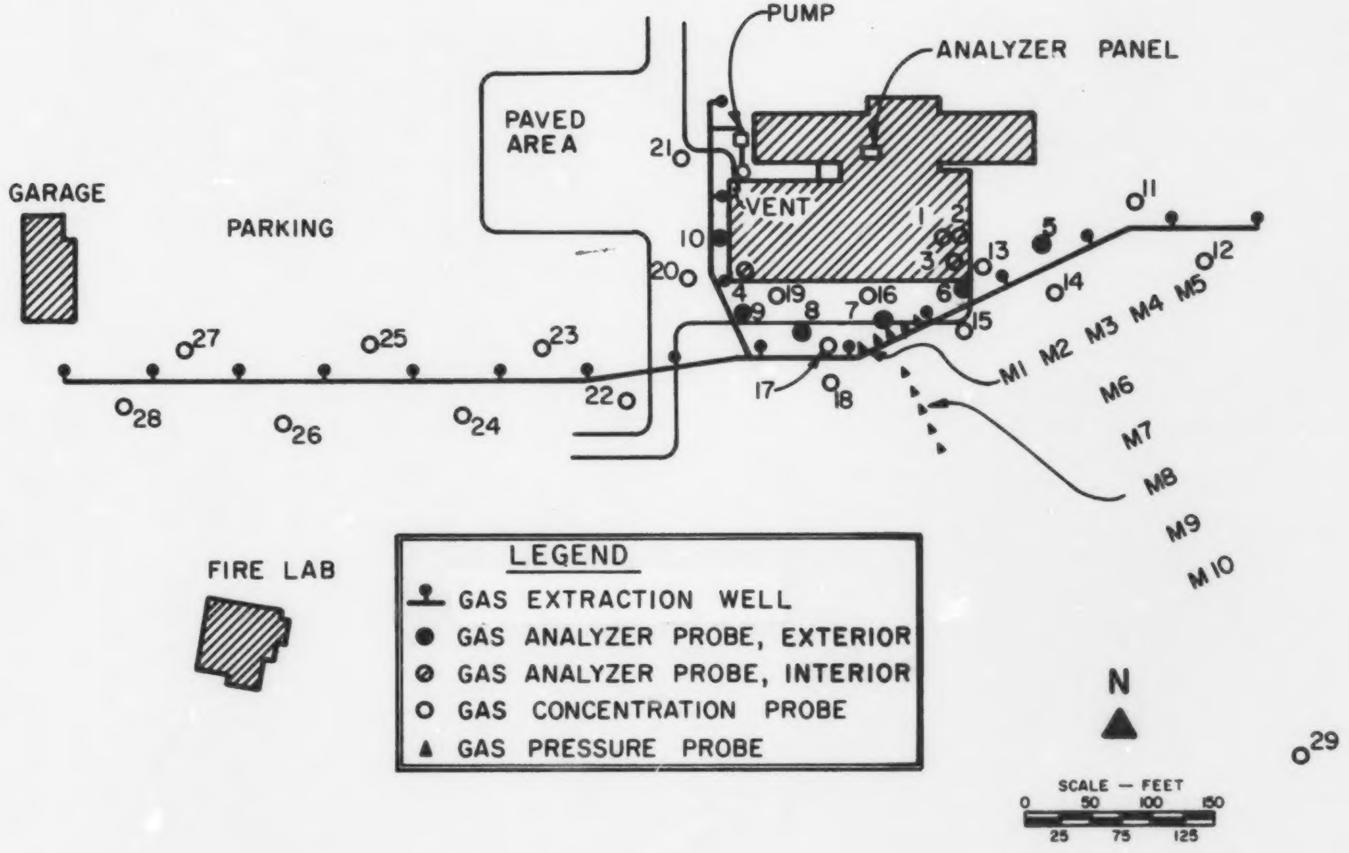
The ultimate purpose of the gas barrier is to reduce gas concentrations in the immediate vicinity of the protected facilities sufficiently below the lower explosive limit to assure their safe use. This parameter is a primary criterion for the barrier system's success under each mode of operation. Measurements of explosive gas concentration can be correlated with such independent variables as flow rate, duration of flow and weather conditions for the purposes of future design considerations.

It is not sufficient to measure gas concentrations in terms of percentage of the lower explosive limit. Concentrations may exceed LEL at the beginning of barrier operation or when test flow rates are too low to reduce all concentrations below the explosive limit. A portable gas analyzer unit (J-W Gas Kit, Model HPK) was used to determine explosive gas concentrations, in percent by volume. When gas concentrations in probes not connected to the barrier monitoring and signalling system fell below the lower explosive limit, readings in terms of percent lower explosive limit were taken with the portable unit. This allowed more sensitivity to variations of concentration at the lower ranges of concentration. The installed gas monitoring and signalling system (consisting of a sampling system, combustible gas analyzer, programmer, control and signal devices and a 10-point recorder) were used to determine gas concentrations (in terms of LEL) from the probe locations serving the system. Locations of probes serving the monitoring and signalling system, as well as those for supplemental evaluations, are shown in Figure 15. Subterranean Probes 5 through 10 (see Figure 14) consist of standard well points driven 10 feet below grade, connected permanently by copper sample lines to the gas analyzer. Access is provided through water-meter-type enclosures.

Pressure Probes

Maintenance of a ubiquitous negative pressure in the vicinity of the barrier is an essential requirement; consequently, it is important to verify the ubiquity of the negative pressure and to measure its variations. Relations between pressure distribution and pressure variation in the soil and with system flow rate and atmospheric conditions help describe the effects of soil properties and gas movement at the Link Road site. Probes were installed to permit pressure determinations at 10- and 20-foot depths at locations shown in Figure 15.

Specially constructed U-tube manometers were used to measure subterranean soil-air pressures at each pressure probe. A schematic drawing of a typical pressure probe installation and manometer is shown in


PUMP
ANALYZER PANEL
PAVED AREA
GARAGE
PARKING
VENT
FIRE LAB
1
2
3
4
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6
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10
11
12
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28
29
M1 M2 M3 M4 M5
M6
M7
M8
M9
M10
N
SCALE — FEET
0 25 50 75 100 125 150
LEGEND
GAS EXTRACTION WELL
● GAS ANALYZER PROBE, EXTERIOR
⊘ GAS ANALYZER PROBE, INTERIOR
○ GAS CONCENTRATION PROBE
▲ GAS PRESSURE PROBE

Figure 15: Probe locations for gas barrier evaluation

Figure 16. In this instance, manometer assemblies were fabricated locally and permanently mounted on plyboard. The manometer assembly was mounted on a cart for transport to each sampling point.

Vacuum Gauges and Taps

Each well is equipped with a vacuum gauge tap so that flow among the barrier wells may be equalized (uniform vacuum) by use of butterfly throttling valves. Consistent recording of vacuum readings and of valve settings at each well are required to provide information for operational and test regimes.

TEST PROCEDURES

Base levels of gas concentration and pressures in the soils were established before any pumping (even for equipment testing) took place. These tests were performed regularly for approximately one month prior to the first activation and operation of the pump. The on-going gas monitoring program continued uninterrupted and readings were obtained on a regular, daily (5 day/wk) schedule, coinciding with gas concentration readings throughout the test period.

Mode I: Low-Flow Pumpage without Surface Seal

The vacuum pump was operated at the lowest flow rate of 160 scfm (corresponding to lowest available speed setting of 585 rpm) for about two weeks. This period was not enough to produce an equilibrium pressure distribution in the soils along the barrier; however, most parameters were approaching steady-state, as shown later under discussion of results. During this period, gas concentration, pressure, flow rate and cumulative volume of gases removed were recorded.

Modes II, III and IV: Varying Flow Pumpage without Surface Seal

After it was ascertained that the system was satisfactorily effective at the minimum pumpage rate, pump speeds were increased for a similar length of time. This sequence could be repeated, if necessary, by step increases in the pump speed (745, 905 and 1,065 rpm) until the pump's ultimate capacity is reached. System flow rates at these pump settings

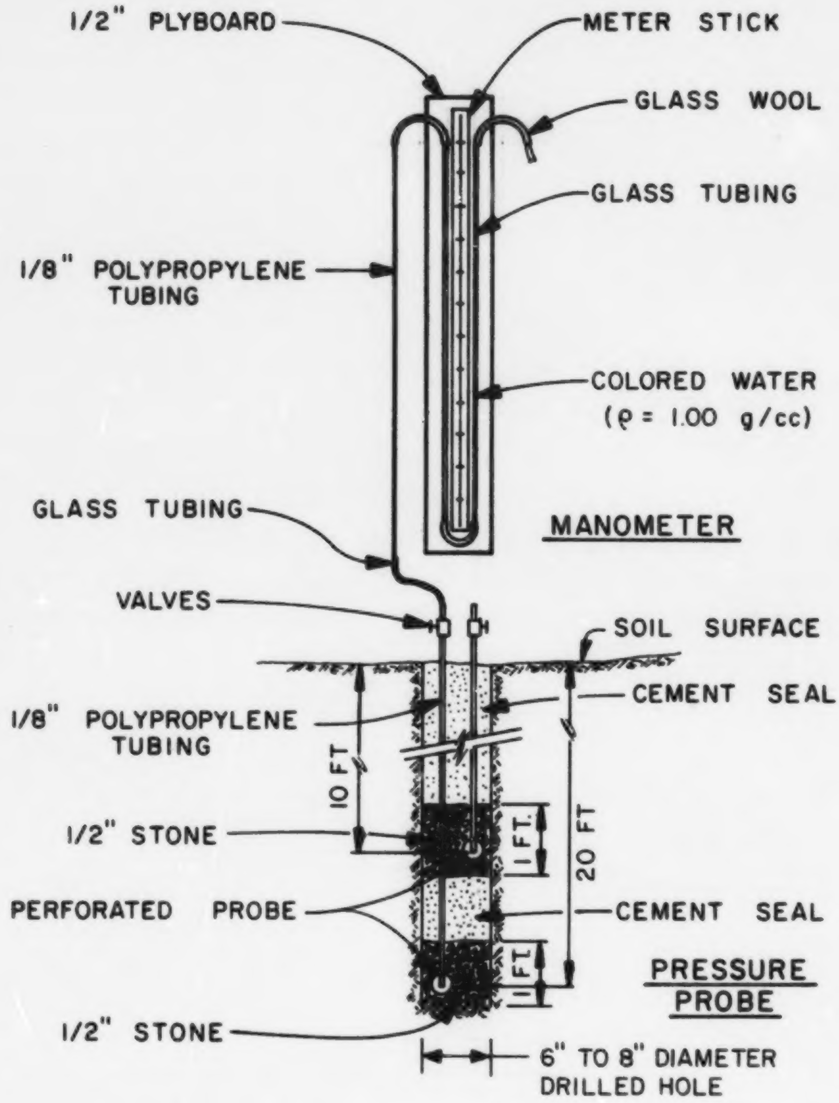

1/2" PLYBOARD
METER STICK
GLASS WOOL
GLASS TUBING
1/8" POLYPROPYLENE TUBING
COLORED WATER
(ρ = 1.00 g/cc)
GLASS TUBING
MANOMETER
VALVES
SOIL SURFACE
CEMENT SEAL
1/8" POLYPROPYLENE TUBING
10 FT
1 FT.
20 FT
1/2" STONE
PERFORATED PROBE
CEMENT SEAL
1 FT.
PRESSURE PROBE
1/2" STONE
6" TO 8" DIAMETER DRILLED HOLE

Figure 16: Pressure probe and manometer detail

were 168, 210 and 250 scfm, respectively. Throughout each test sequence, all parameters were measured and recorded.

Maintenance of a ubiquitous negative pressure and no passage of landfill gas to the protected side of the barrier (when the barrier is operating at low flow with no sealants) was used as a positive criterion of successful performance.

Mode V: Contingency Tests for Surface Seal with Varying Flow

An ultimate back-up provision, the necessity for which appears highly unlikely, is application of the designed surface seal along the barrier. Application of the surface seal will make it possible to effect confined flow conditions, with no flow of atmospheric gases into or between wells along the barrier. Standard asphalt paving is considered most appropriate as a seal, but application of a seal was not required or tested in the evaluations conducted and reported herein.

The test program for such a contingency condition was designed to give the maximum amount of data for future design purposes as well as to effectively evaluate this unique feature, not common to existing barriers. While the seal is being installed, pumping should continue at the lowest design rate and complete data collection should be conducted. A chronicle of the progress of seal applications should be kept to correlate the time of seal placement with the reductions in gas concentrations or increases in negative pressure.

The seal can be placed in successively increasing widths and lengths (e.g., exclude western leg), allowing sufficient time between dimensional increments to permit equilibration of the flow and pressures. Incremental seal application and concurrent lapses of time will be dependent on available test results, equipment availability and logistics.

In the highly unlikely event that the low-flow and surface-seal combination system proves unsatisfactory (under some severe combination of conditions, certainly not expected at the Link Road site), high-flow pumps may be installed and their performance tested in much the same general pattern as prescribed above for the low-flow system. The success of high-flow ventilation barriers has already been demonstrated elsewhere (Reference 27).

Noise Survey

Noise levels resulting from operation of the vacuum pump equipment installed for gas evacuation were measured by R. J. Reynolds Tobacco Company personnel on 15 May 1974 for the City of Winston-Salem. The objectives of the survey were to determine if the vacuum pump produced noise levels which would be annoying and generate objectionable complaints and to determine if the noise levels during operation were hazardous to human hearing. On that basis, the procedure used was to measure the noise levels produced by the vacuum pump and to measure the prevailing daytime background noise levels with the vacuum pump off.

The following instruments were used during the noise survey: General Radio Octave-Band Noise Analyzer, Type 1558-BP, Serial No. 2155; and General Radio Piezoelectric Microphone Assembly, Type 1560-P6, Serial No. 1614.

The A-weighted sound level and octave-band sound pressure levels were measured at two positions. The pump speed was 1,065 rpm (motor speed 1,750 rpm). All measurements were taken at a height of four feet above the ground. The first measurement was taken close to the pump. The microphone was located three feet north of the vacuum pump gearbox. The second measurement was taken 10 feet north of the vacuum pump gearbox at the sidewalk. With the vacuum pump off, background noise levels were also measured three feet north of the vacuum pump gearbox during normal and peak traffic conditions on Silas Creek Parkway.

The A-weighted sound levels obtained were used to evaluate noise induced hearing hazard. The A-weighting network has a frequency characteristic similar to that of the human ear, i.e., both are more sensitive to middle frequencies than very high or very low frequencies. The octave-band frequency analysis, i.e., the distribution of sound pressure level in the nine preferred octave bands with center frequencies from 31.5 to 8,000 Hz provides additional information concerning the character of the noise and for estimating subjective annoyance effects such as speech interference.

RESULTS

A large volume of data on gas concentrations and pressures was generated during the course of system testing and evaluation, under two modes of operation, lasting about three months. These data firmly corroborate the theoretical computations which were used as a basis for the conceptual design of the gas migration barrier. Because most data are confirmatory, only representative samples of data showing trends over time and space are presented in this section. The remainder of the data are not graphically presented in order to maintain simplicity and prevent repetition and confusion of the presentation.

Records obtained from flow rate meters, gas concentration probes and pressure probes, and those obtained less frequently from other instruments were analyzed and evaluated promptly. Because many decisions regarding additional construction and operation of the barrier system had to be based upon these results, prompt and proper analysis and careful evaluation of data were conducted as the data were collected and as system operation continued during the test period. Overall evaluation criteria on each of the parameters are outlined below.

Combustible Gas Concentrations

The most important parameter, from the point of view of human safety from explosion hazards, is concentration of explosive gases on the protected side of the barrier. Early results, after initiation of pumping, indicated a definitive trend, with gas concentrations in the protected areas rapidly falling with time. The trends continued at all probe locations with a firm trend toward zero readings throughout the monitoring period. Trends of average combustible gas concentrations are shown on Figure 17 for shallow (10 feet) probes and deep (15 feet) probes on both sides of the barrier. In order to maintain comparability of the two sets of data, only

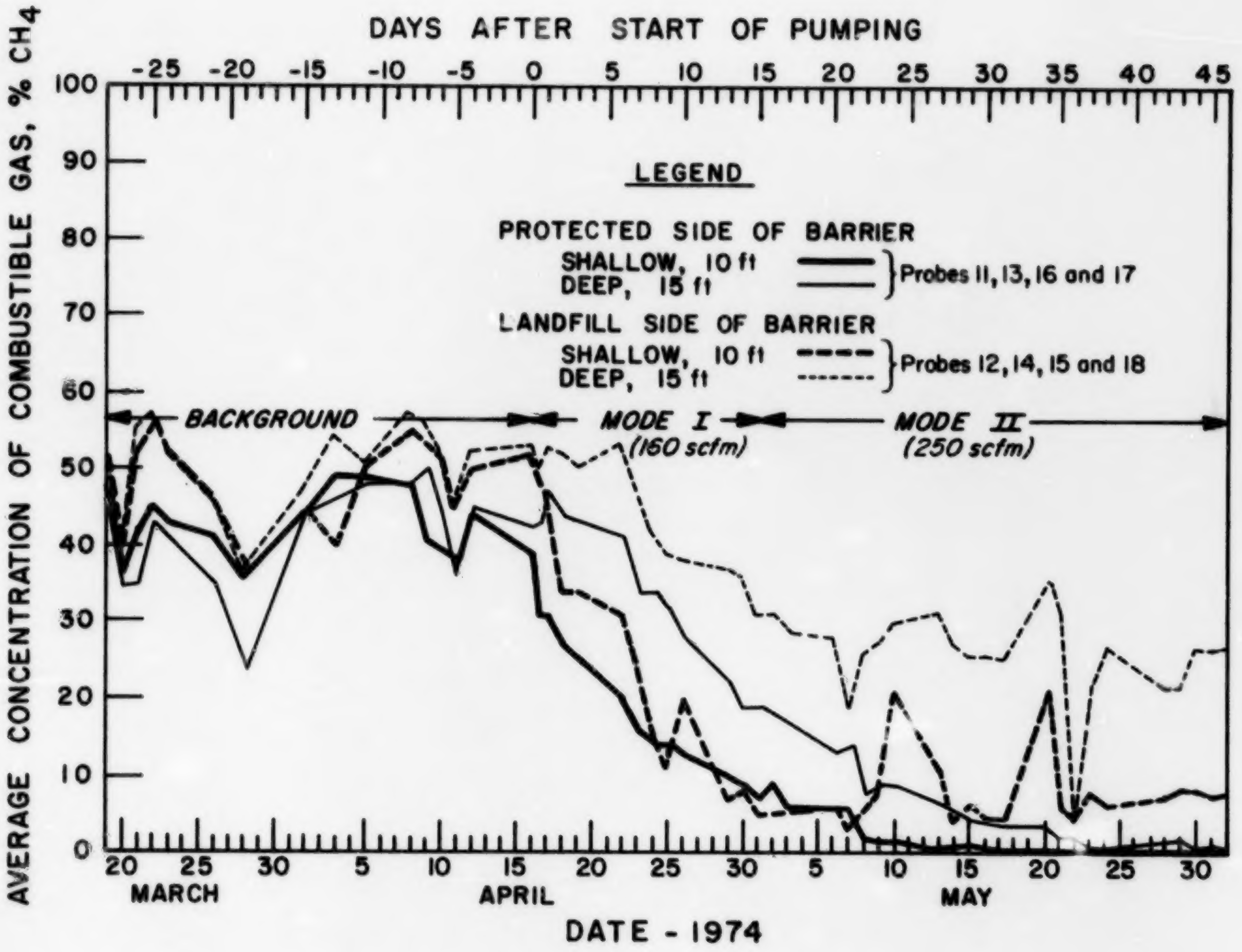


Figure 17: Average concentration of combustible gas on either side of gas migration barrier prior to and during operational modes

those data obtained from Probes 11, 13, 16 and 17 (Armory side) and 12, 14, 15 and 18 (landfill side) were utilized to obtain the averages plotted on Figure 17. Other data present a similar picture. From probes located inside the buildings, readings of percent of the lower explosive limit (i.e., percentage of five percent methane by volume in air), recorded with automatic equipment, were obtained and plotted as shown on Figure 18. Percent lower explosive limit (LEL) is a very sensitive and highly refined measure of safety or lack of it in an occupied space. (For example, 25 percent of LEL, at which point alarm systems are activated, corresponds to a methane concentration in air of only 1.25 percent by volume.)

Gas chromatographic analyses of combustible and other gases sampled at the pump discharge and at selected probes provided additional data during the evaluation period. Concentrations of oxygen, nitrogen, methane and carbon dioxide in these samples were measured. Table 10 shows the chromatographic analysis for the pump discharge and Table 11 for other selected probes from the deep (15 feet) access points. As expected, the gas mixture pumped from the volume of soil on both sides of the barrier was rich in methane and carbon dioxide at the beginning of the operation. As pumping continued, evacuation of combustible gas from the protected side of the barrier and admission of atmospheric air from both sides caused a gradual decline of CH_4 and CO_2 concentrations with a simultaneous increase in O_2 and N_2 concentrations. A similar trend from gas chromatograph concentrations at the selected probes was not as evident during the brief time and limited extent of gas chromatographic analyses, in the early period of barrier operation, but pronounced reduction in concentrations at probes near the barrier were verified by gas analyzer readings as pumping continued. Concentrations at most probes had declined to or near zero levels, with lowered gas concentrations persisting at a few deep probes, primarily on the landfill side.

Flow from Individual Wells

A primary parameter in the operation of the barrier system at the Link Road site is rate of flow of the gas mixture. It is imperative that flow from individual wells be maintained uniform along the entire

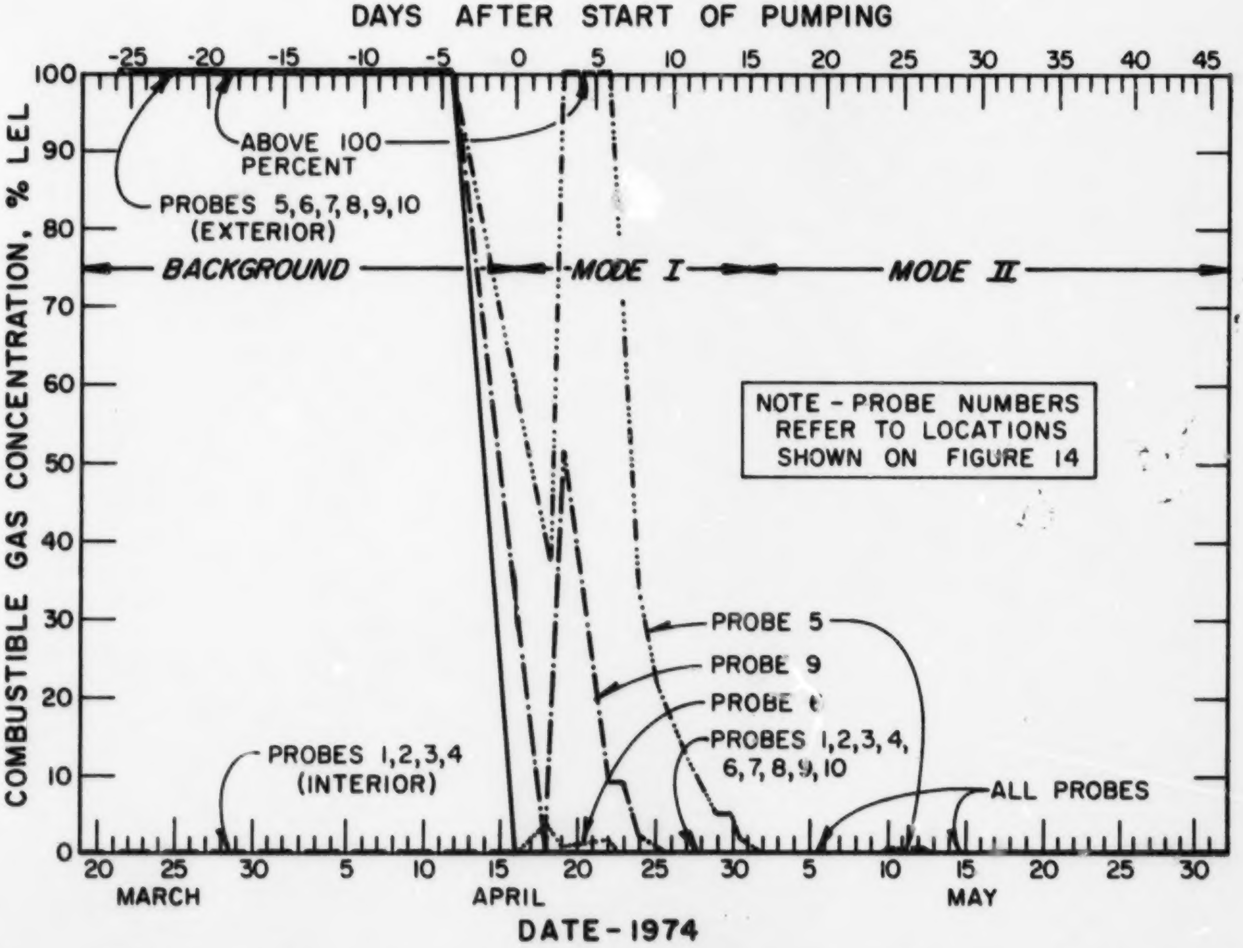


Figure 18: Percentage of lower explosive limit at individual probes in and near buildings prior to and during barrier operational modes.

Table 10. GAS CHROMATOGRAPHIC ANALYSIS OF BARRIER PUMP DISCHARGE GASES

DATE	Gas composition, % by volume			
	O_2	N_2	CH_4	CO_2
16 Apr 74	7.6	44.7	24.4	23.0
18 Apr 74	3.4	43.4	31.1	24.7
19 Apr 74	7.4	47.4	20.3	24.6
22 Apr 74	9.0	48.5	20.6	29.5
23 Apr 74	7.6	51.2	19.8	20.7
24 Apr 74	5.1	54.3	20.6	20.0
25 Apr 74	5.5	54.5	19.8	20.8
26 Apr 74	5.8	50.0	22.8	22.2
29 Apr 74	3.1	61.0	14.4	20.6
30 Apr 74	15.2	63.0	11.2	8.8
1 May 74	12.5	62.9	7.5	17.0
2 May 74	10.7	70.6	8.1	10.0
3 May 74	21	78	Trace	Trace
6 May 74	20.4	76.8	1.2	1.0
8 May 74	18.4	76	2.6	2.4
10 May 74	19.4	75	2.6	2.2
13 May 74	8.6	68	11.8	11.1
15 May 74	9.0	67	11.3	11.9
17 May 74	13.5	74	7.0	6.7

Table 11. GAS CHROMATOGRAPHIC ANALYSIS OF SAMPLES FROM SELECTED PROBE LOCATIONS*

	Gas composition, % by volume			
DATE	O_2	N_2	CH_4	CO_2
Probe 11D				
24 Apr 74	9.2	30.2	37.0	22.8
30 Apr 74	2.8	18.7	45.1	33.0
2 May 74	6.3	35.2	30.5	28.0
Probe 12D				
3 May 74	4.1	10.6	53.1	31.3
6 May 74	5.1	20	43.8	30.7
Probe 24D				
18 Apr 74	4.0	13.9	53.8	25.6
19 Apr 74	5.2	9.1	55.0	30.4
22 Apr 74	1.2	10.1	62.8	26.0
23 Apr 74	8.6	35.0	35.7	20.2
25 Apr 74	3.0	20.4	52.9	24.7
26 Apr 74	4.5	26.8	46.5	21.6
1 May 74	3.8	33.1	36.4	26.1

*Probe locations 12 and 24 are on the landfill side of the barrier, Probe 11 is in the gravel-surfaced parking lot, inside the barrier and west of the Armory. See Figure 15.

barrier for the duration of its operation. An unusually high flow in a well usually indicates leakage of air or a relatively high-permeability medium surrounding the well. In such cases, the valve at the well head was partially or totally throttled so that the well would not interfere with the operation of other wells. An unusually low flow may indicate a low permeability medium around the well. Such an observation was not recorded during the conduct of the test procedure.

Direct flow measurement on each well head was not practical. However, an indirect, though accurate, measure of flow was obtained from relative vacuum readings. A portable vacuum gauge was used on quick-connect nipples provided on each well head. Excessively low vacuum readings were encountered on three wells (Wells 11, 12 and 13, Figure 12) located in an area where higher soil permeabilities were suspected from earlier soil tests. The rushing sound of air moving through these particular well heads emphatically corroborated that excessive flows were taking place from those wells. Therefore, in order to maintain as high a vacuum as possible and to preserve the uniformity of flow from other wells, the valves on the three wells were closed. While this modification may reduce effectiveness of the barrier in the vicinity of the wells, flow at the remaining wells is increased thereby. No potential for hazardous gas accumulation existed nearby so further modification, such as application of a surface seal, was not attempted.

Flow rates from the entire system were 160 and 250 scfm during operational Modes I and II, respectively. These flows correspond to average flows per well of 11 and 17 scfm, respectively. It should be noted that the flow rates found satisfactory in the tests are far lower than those reported for other existing forced-ventilation operating systems.

Pressure Distribution

All pressure measurements were made relative to the atmosphere. It was found that atmospheric pressure variations were experienced almost immediately at the depths manometer probes were installed. In view of the wide atmospheric pressure variations encountered, as shown in Figure 19, and because flow, in a given area, occurs in direct response to

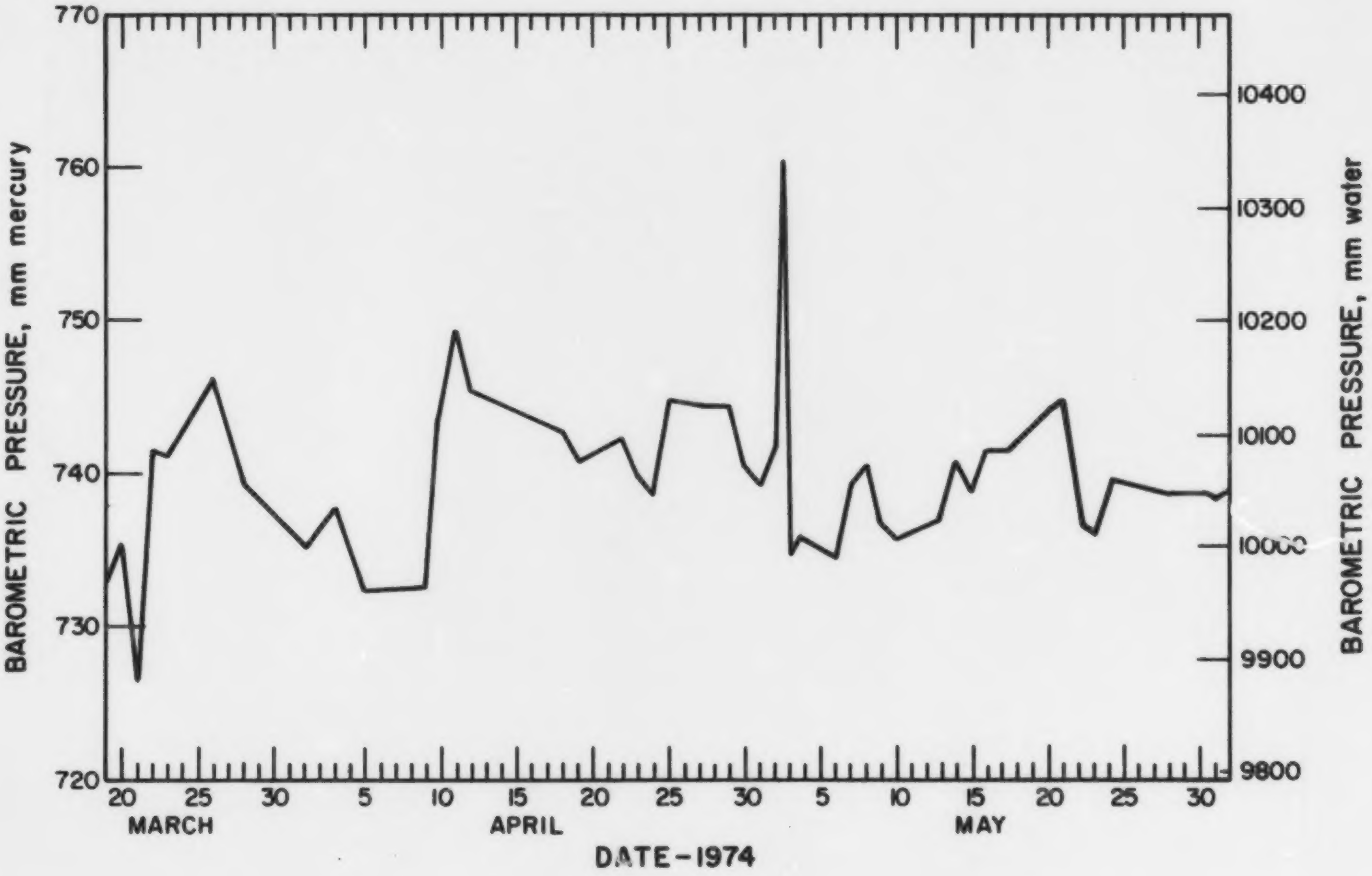


Figure 19: Variations of barometric pressure during the barrier test period

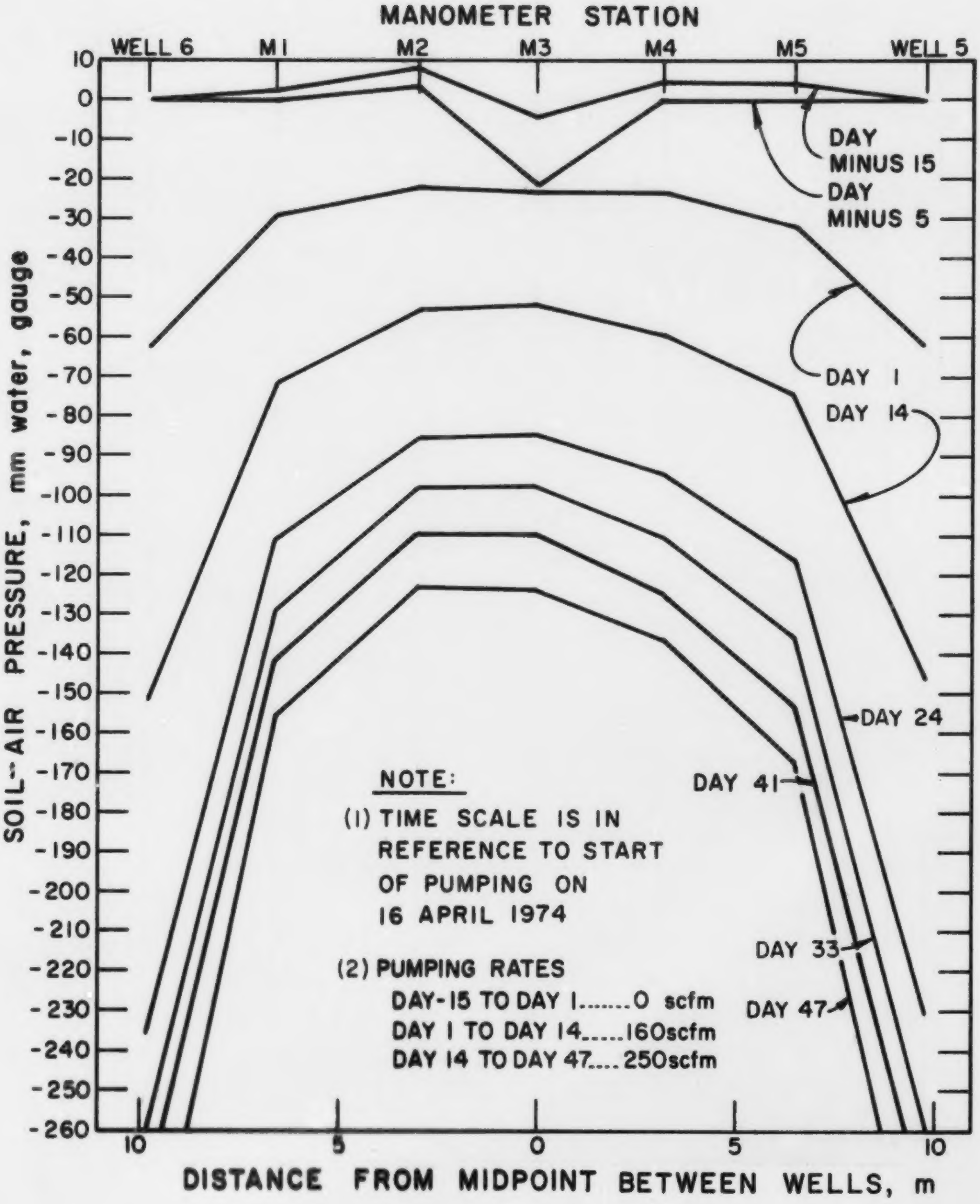
gradients of relative pressure, use of absolute pressures was avoided. Typical draw-down curves between wells were obtained before and during the test period as pumping progressed. Pressure distributions at 20-foot depth between Wells 5 and 6 at selected points in time are shown on Figure 20. It is noteworthy that a ubiquitous negative pressure at all points along the barrier was obtained immediately after pumping began at the 160-scfm rate and that the negative pressures at all points between wells, particularly midway, continued to increase significantly, particularly at the 250-scfm rate.

The increases in negative pressure with time at the deep probe level at the M6 through M10 stations at a point midway between wells and at increasing distances from the line of wells are illustrated in Figures 21 and 22, respectively. The significance of the drop in pressure over time is dramatically exhibited in a statistical test of the differences between average pressure before pumping and that during each mode of operation of the barrier system. The range, average, standard deviation and statistical significance test of the differences for each mode of operation throughout its duration are shown on Table 12. It is noted that the influence of the barrier significantly extends to a distance of at least 18 meters (about 60 feet) from the barrier in both operating modes (160 and 250 scfm).

Noise Levels

The Federal Occupational Safety and Health Act of 1970 (OSHA), using the Walsh-Healy Public Contracts Act, paragraph 50.204.10, Safety and Health Standards for Federal Supply Contracts, specifies the maximum number of hours per day an employee may be exposed as a function of the A-weighted sound level when measured with the A-network of a standard sound level meter at slow response.

According to the regulation, the noise level limit is 90 dB(A) for an eight hour per day exposure over a working lifetime. For noise levels lower than 90 dB(A), longer exposure times are permitted. The converse is also true.



NOTE:

(1) TIME SCALE IS IN REFERENCE TO START OF PUMPING ON 16 APRIL 1974

(2) PUMPING RATES
DAY-15 TO DAY 1.......0 scfm
DAY 1 TO DAY 14......160scfm
DAY 14 TO DAY 47.....250scfm

Figure 20: Drawdown curves between barrier wells 5 and 6 during barrier test period

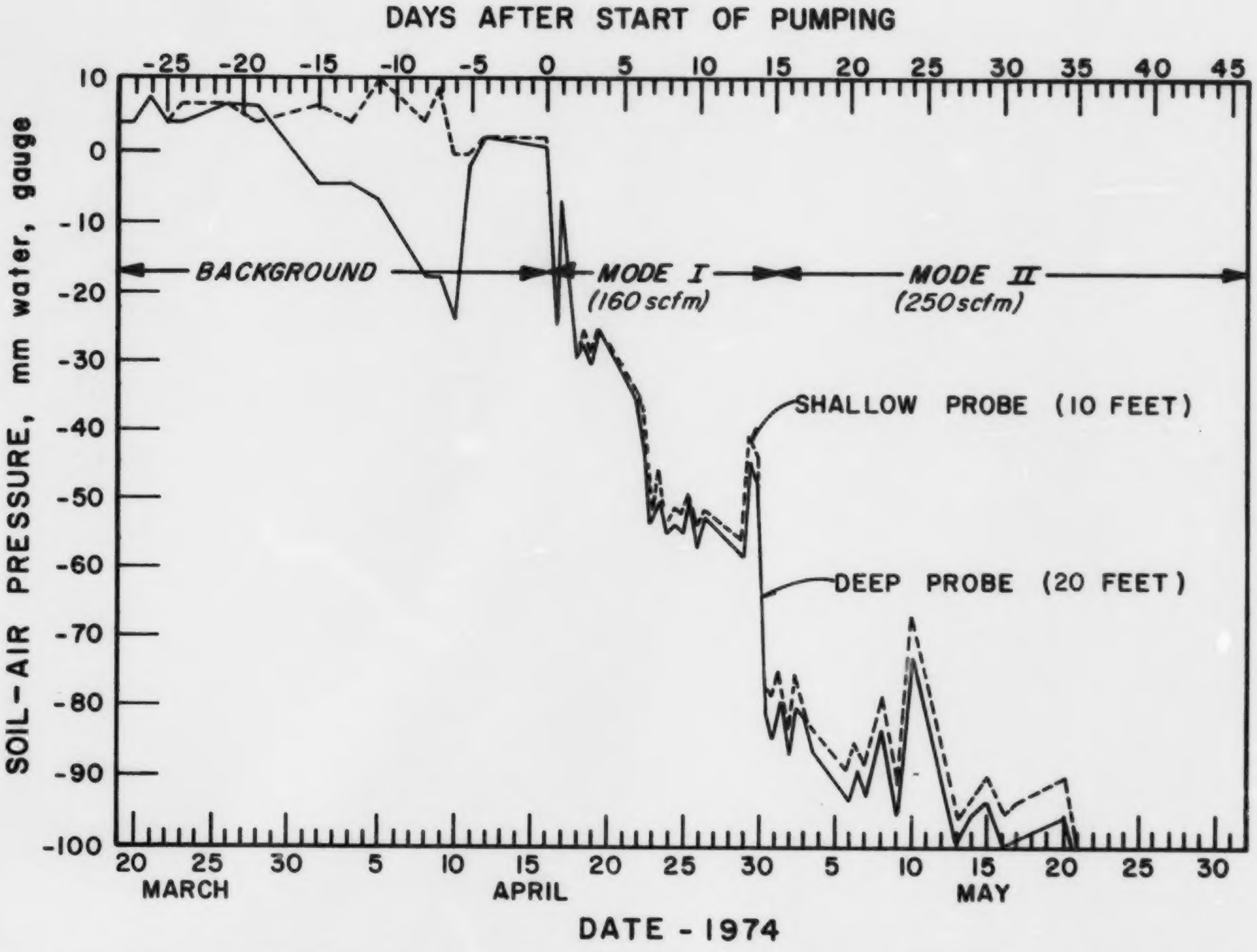
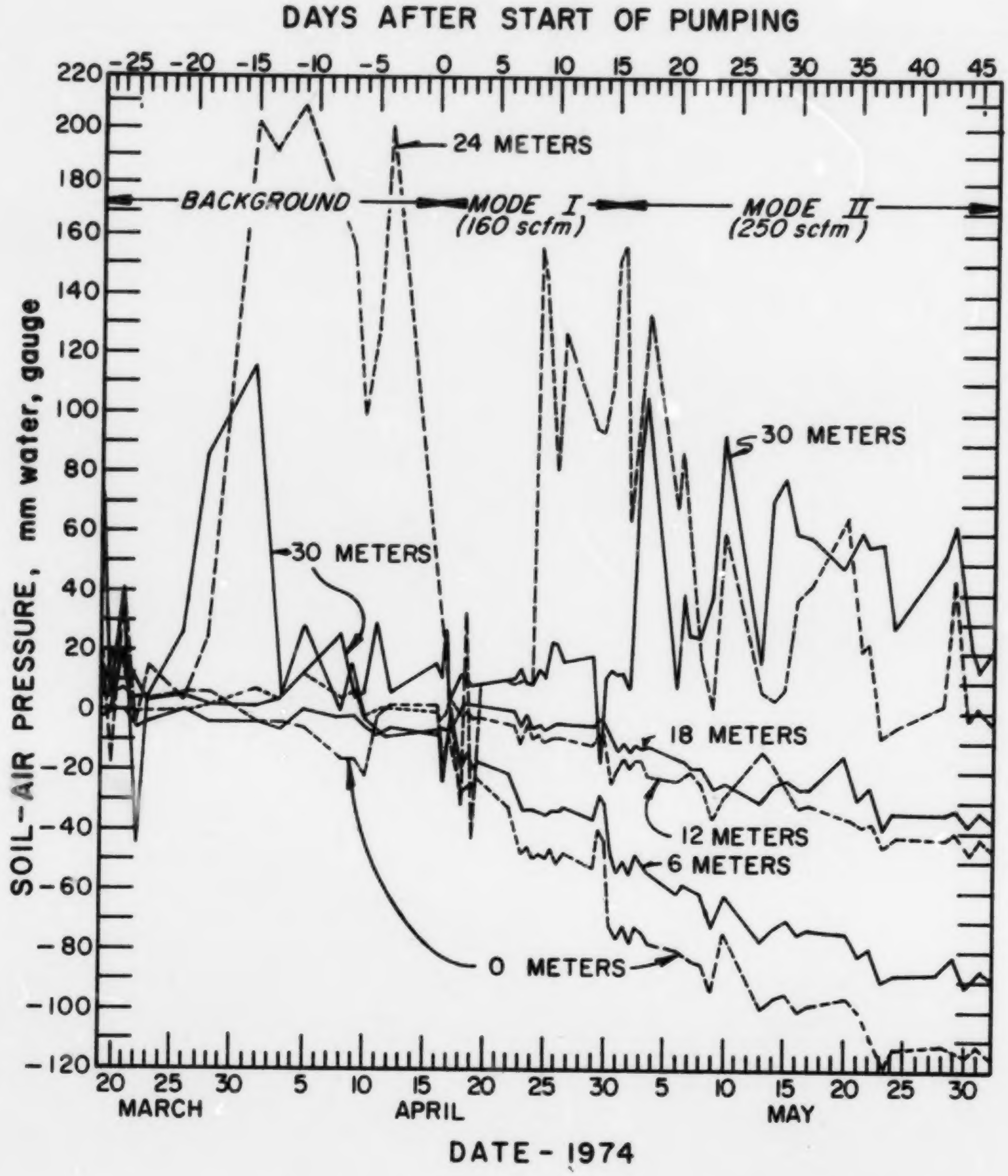


Figure 21: Relative pressure at two depths midpoint between barrier wells 5 and 6 during barrier test period



NOTE: PRESSURE READINGS WERE OBTAINED FROM MANOMETER PROBE LOCATIONS M6 THROUGH M10 (FIGURE 15), ESTABLISHED AT 6-METER INTERVALS, IN A LINE PERPENDICULAR TO THE LINE OF THE BARRIER AND EXTENDING INTO THE LANDFILL FROM A POINT MIDWAY BETWEEN WELLS 5 AND 6

Figure 22: Relative pressure at various distances from barrier during the test period

Table 12. STATISTICAL DATA ON COMPARATIVE EFFECTIVENESS OF SOIL-AIR PRESSURE REDUCTION AT VARIOUS DISTANCES FROM BARRIER UNDER TWO OPERATIONAL MODES

Manometer station	Distance from barrier, m	Distance from barrier, ft	Pressure range, mm H_2O			Mean pressure, mm H_2O			Standard deviation			t value	
			Background	Mode I	Mode II	Background	Mode I	Mode II	Background	Mode I	Mode II	Mode I	Mode II
M3	0	0	+7 to -22	-2 to -72	-71 to -124	-2	-42	-97	9	12	17	-10.6[a]	-20.03[a]
M6	6	19.7	0 to -8	-14 to -47	-48 to -97	-4	-29	-73	3	8	15	-11.1[a]	-16.89[a]
M7	12	39.4	+12 to 0	0 to -25	-13 to -54	5	-8	-29	9	6	13	-5.25[a]	-9.33[a]
M8	18	59.0	+30 to 8	0 to -8	-9 to -47	6	-3	-25	10	3	12	-8.60[a]	-10.52[a]
M9	24	78.7	+214 to -18	+157 to -155	+156 to -13	95	43	+39	87	79	50	+1.79[b]	-1.07[b]
M10	30	98.4	+116 to -44	+33 to -17	+105 to +7	27	13	+40	41	10	28	+1.42[b]	-1.29[b]

[a] Significantly different from background conditions at the 99 percent level of confidence.

[b] Not significantly different from background conditions at the 99 percent level of confidence.

By way of comparison, the A-weighted sound levels measured at three and 10 feet from the vacuum pump gearbox operating at maximum speed (1,065 (1,065 rpm) were 86 dB(A) and 75 dB(A), respectively. Results of the noise analysis are presented in Figures 23 and 24. Thus, operation of the vacuum pump does not present a serious hazard to human hearing. Since the pump operator is not required to spend a considerable length of time near the unit, personal ear protective devices, such as ear plugs and ear muffs, are not required.

A further evaluation of the pump noise levels at the sidewalk was made due to the possibility of annoyance when the vacuum pump noise interferes with speech intelligibility. The Preferred Speech Interference Level (PSIL) is a good guide to the interfering effect of an intruding noise on speech.

The extent to which a steady continuous noise interferes with speech communication depends upon the distance between the speaker and listener at various levels of voice effort. The PSIL is the arithmetic average of the sound pressure levels in the three octave bands, with center frequencies at 500, 1,000 and 2,000 Hz. The interference levels are for average male voices with speaker and listener facing each other, using unexpected word material. It is assumed there are no nearby reflecting surfaces that aid the speech sounds.

The PSIL of the noise produced by the vacuum pump at the sidewalk is 70 dB. The average person would need to shout to make himself understood at a distance of six feet with the vacuum pump in operation. A comparison of the PSIL produced by the vacuum pump (70 dB) and the PSIL of the prevailing background noise in the area during normal traffic conditions (54 dB) indicates that the average person would be understood at a distance up to about six feet using a normal conversational voice level with the vacuum pump off, as shown in Figure 25.

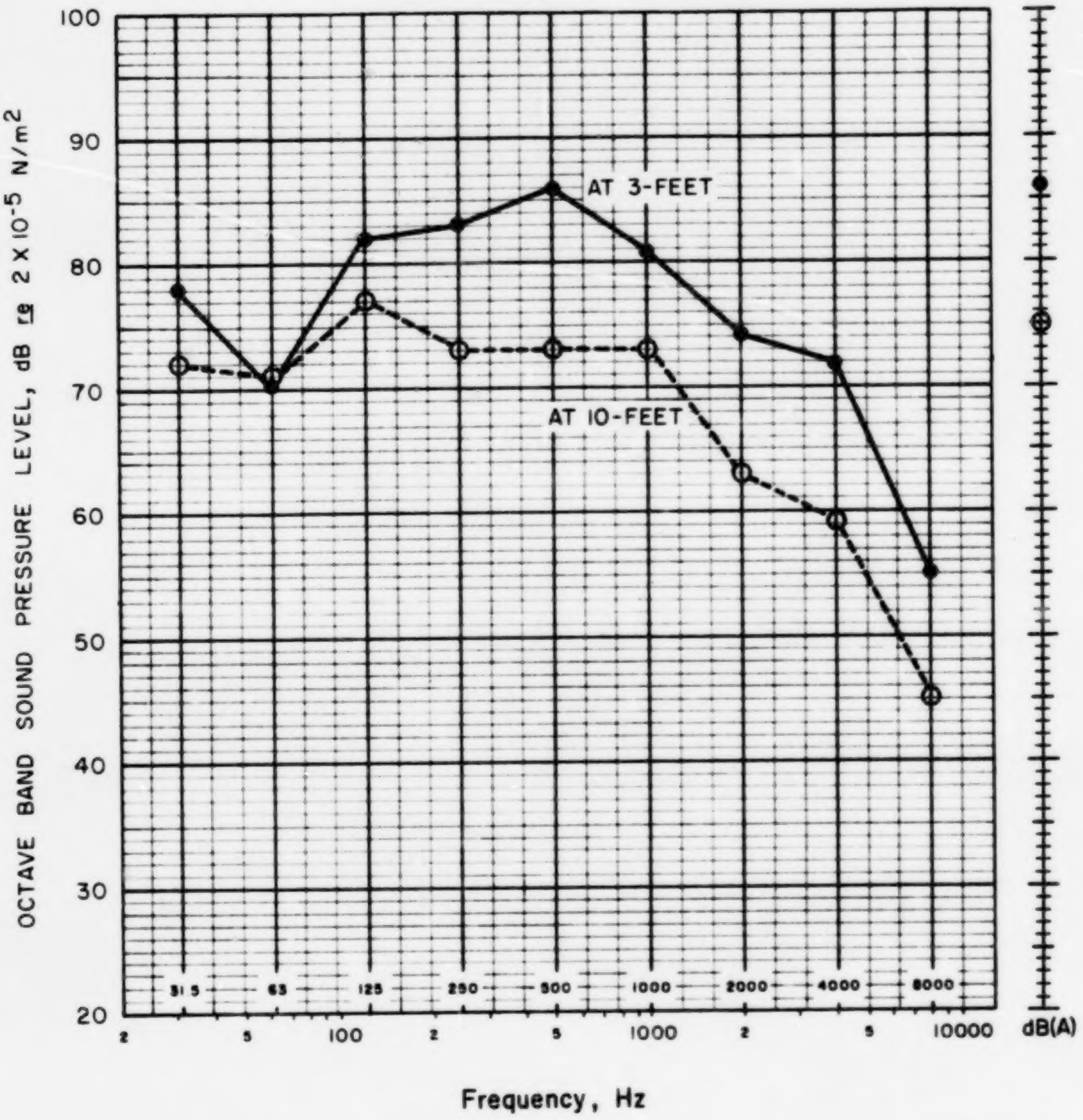


Figure 23: Frequency analysis of noise produced by vacuum pump

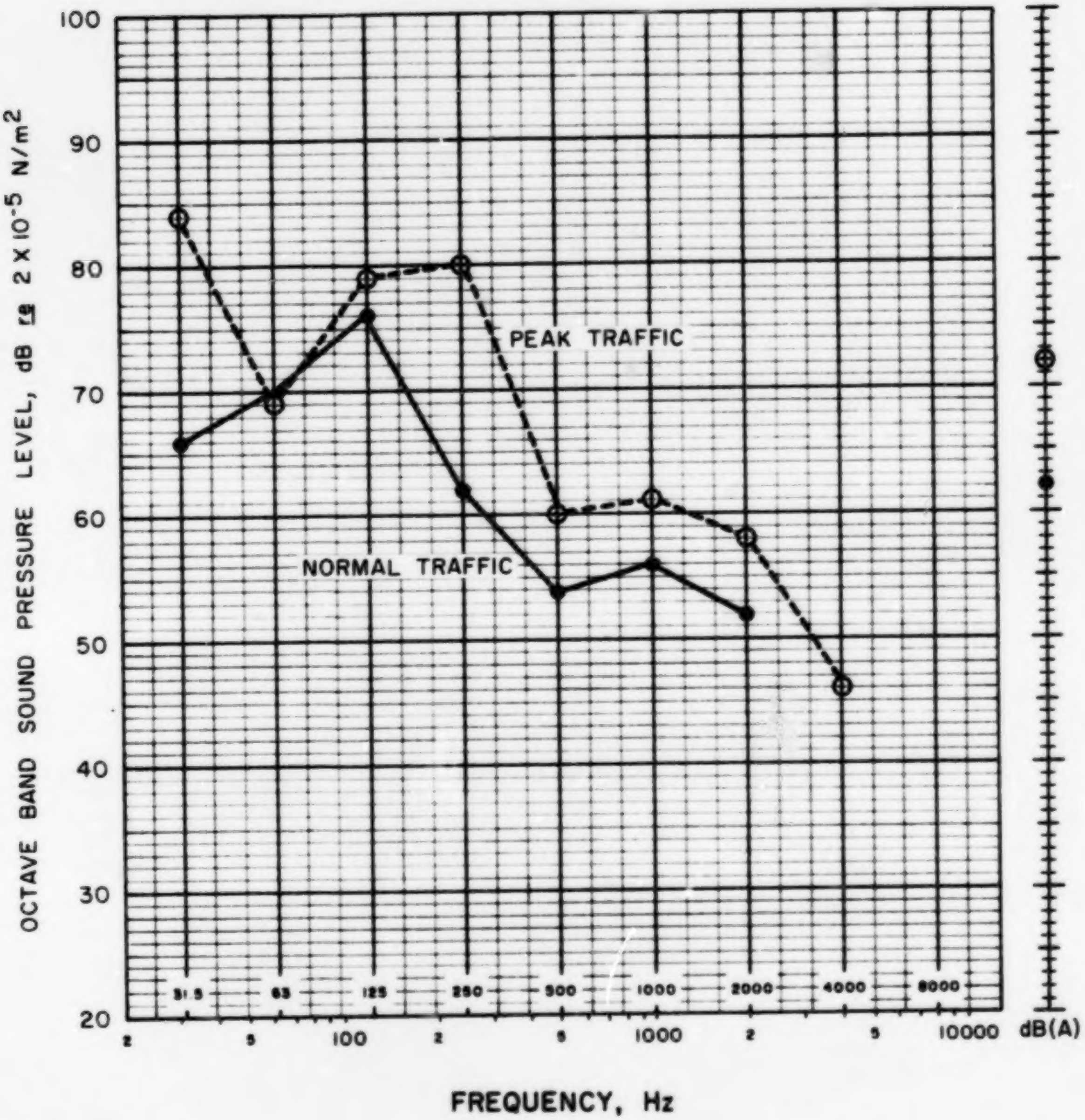


Figure 24: Frequency analysis of background noise measured three feet from vacuum pump gearbox

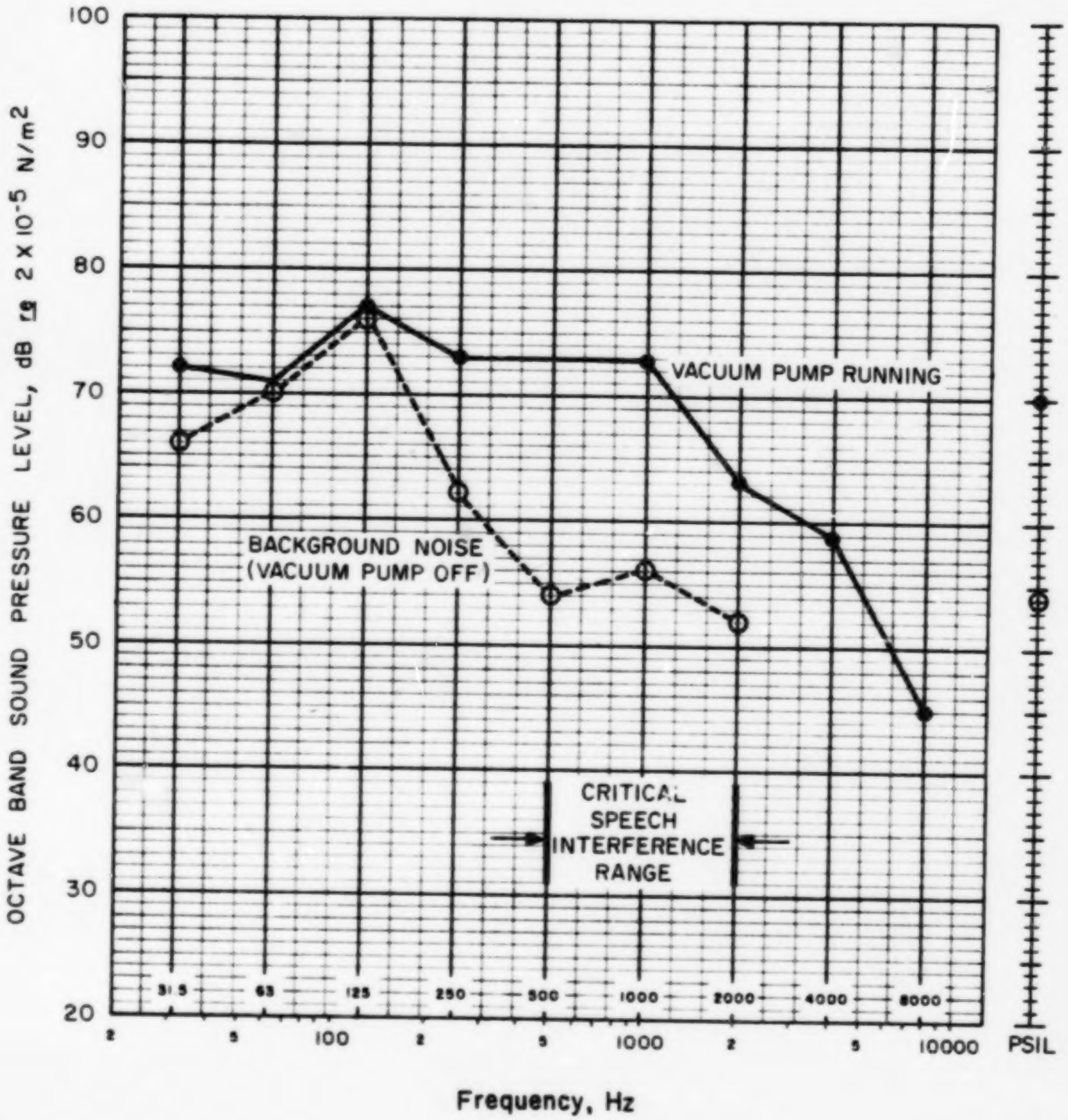


Figure 25: Comparison of vacuum pump noise levels measured at 10 feet to the background noise levels measured during normal traffic conditions

EVALUATION OF RESULTS

Safety for Occupancy

The combustible gas concentration profiles, presented in Figures 17 and 18, show conclusively that the system is providing and maintaining gas concentrations at or near zero inside the barrier and in occupied spaces under the least intensive operating mode. If careful monitoring confirms that these conditions continue to obtain over a period of months, the Armory should then be free from explosion hazards and suitable for normal occupancy and use. That adequate protection is apparently provided is best evidenced by the plot of percent lower explosive limit at all inside monitoring probe locations before and after the start of the system, as shown on Figure 18. Probes located inside the Armory (Probes 1, 2, 3 and 4) consistently recorded zero LEL readings throughout the test period. Whereas combustible gas concentrations were uniformly above 100 percent LEL before the start of the system at all probes outside the Armory, they dropped precipitously upon start of the pumping process. The sharp, but ephemeral, resurgence of gas concentrations at two outside probes (Probes 5 and 9) after the initial drop, is attributed to the arrival of gases that had previously moved under and beyond the Armory. It is expected that after all the explosive gas on the protected side is extracted there will be no more source of supply of gas, north of the barrier, to give rise to any further such peaks. With the pumpage rates of 160 to 250 scfm used, it is estimated that complete removal was accomplished in the duration of the test period.

A comparison of average combustible gas concentrations on both sides of the barrier at two depths, as shown in Figure 17, is revealing. While combustible gas concentrations at both depths (10 and 15 feet from the surface) declined to zero on the protected side of the barrier, those on the landfill side declined to values above zero. This trend is wholly expected due to the continuous generation of combustible gas in the landfill. The decline in concentration is due to admixture of progressively greater amounts of air entering from the surface. This phenomenon also explains the faster rate of decline of combustible gas concentration from the shallower probes than from the deeper ones on both sides of the barrier. After several months, when equilibrium conditions are fully established, the average concentration of combustible gas from the probes on the landfill side of the barrier--at any given pumpage rate--may be used as an index to the approximate gas generation rates in the fill.

Barrier Effectiveness

While gas concentration data help establish the effective operation of the system, pressure distributions reveal the degree of success of the barrier, its extent of influence and the need, if any, for its improvement. The "draw-down" curves in Figure 20 show the gradual lowering of pressure (increasing negative pressures) at all points between wells. While a minimal pressure drop of a few millimeters of water at the midpoint between wells would be sufficient to ascertain protection, negative pressures of above 100 millimeters water obtained under Mode II operation of the barrier provide a very high factor of safety. The pressure decline over the test period at the critical midpoint between wells is illustrated on Figure 21. The high negative pressures obtained virtually guarantee existence of ubiquitous negative pressures throughout the length and depth of the construction barrier.

Extent of Influence of Barrier

A very significant question in the design of new barrier systems is the radius of influence of wells along the barrier. This parameter helps establish maximum spacing of wells, flow rates to be employed and, in some cases, the need for a surface seal along the barrier. The extent of influence of the barrier can be readily visualized from Figure 22 in which declines in pressure are illustrated as a function of time from the start of operations and distance from the barrier. Although only the pressure readings at the deeper (20 feet) probe locations are shown, the trends are the same for the shallow probes, albeit more pronounced. It is evident from Figure 22 and from statistical analysis presented in Table 12 that the influence of the barrier extends to at least Station M8, approximately 60 feet from the barrier. Thus, it may be surmised that under existing flow conditions, a well spacing greater than the existing 67-foot interval may be permissible. Conversely, it is evident that lower flow rates can be effective in providing the necessary protection with the existing spacing.

Noise Levels

The pump motor does not present a hearing hazard and does not contribute any additional neighborhood noise at the property line, located more than 50 feet from the pump. There is some noise at the sidewalk directly in front of the pump. However, this should not present a public hazard because people are not expected to be working for long periods in that area. The only person who would be close to the pump at any time is the operator. That person is not required to spend a considerable length of time near the equipment during normal operation.

Power Requirement and Cost

The major component of the barrier system requiring power is the motor driving the vacuum pump via the variable-speed sheave and pulley system. Power requirement for the pump was computed directly, using actual voltage and current measurements during operation at the two extremes of the pump speed range. Power requirement for the gas analyzer sampling pump is relatively minor. It was calculated using a similar procedure. Unit power cost at the time of these computations was $0.0251/kw-hr. The power required and its cost at the two speed extremes are presented in Table 13.

Table 13. POWER REQUIREMENTS AND COSTS FOR GAS MIGRATION BARRIER SYSTEM

	Pump speed, rpm			
	700		1050	
Unit	Power, kw	Cost, $/yr	Power, kw	Cost, $/yr
Motor	3.229	697	4.835	1,044
Analyzer	0.918	198	0.918	198
Total	4.147	895	5.753	1,242

Barrier System Cost

The total construction cost for the barrier system was $88,100, which consisted of $64,400 for the barrier and $23,700 for the monitoring equipment.

The itemized costs for various elements of the gas barrier system, as constructed, are presented in Table 14, which also indicates the corresponding estimated costs used in the evaluation of alternatives.

Table 14. COMPARISON OF ACTUAL AND ESTIMATED CONSTRUCTION COSTS OF GAS BARRIER SYSTEM

	Cost, dollars	
Element	Actual	Estimated
Gas wells	19,800	17,000
Manholes	7,380	6,100
Suction header, 8 in.	24,970	8,900
Vacuum pump	12,250	8,000
Monitoring system	(23,700)	-
Total barrier	64,400	40,000

The greatest discrepancy between actual and estimated costs is the much higher (more than twofold) actual cost of the eight-inch diameter polyvinyl chloride suction header. The higher actual costs in all other elements of the system can be attributed to the high rate of inflation that occurred between the time of estimation and the time of procurement and construction.

CHAPTER IX

TECHNIQUES FOR EVALUATING SOLID WASTE LANDFILLS WITH REGARD TO GAS MIGRATION

MINIMIZING ADVERSE EFFECTS OF GAS PRODUCTION AND MIGRATION

Decomposition gases are a normal, expected consequence of land disposal of solid wastes. Sanitary landfill procedures will necessarily establish anaerobic conditions; consequently, provisions should be made to control the migration of the gases, particularly methane. Certain precautions or provisions can be taken to minimize adverse effects by proper site selection and by the design, construction and operation of the sanitary landfill. In general, open burning dumps pose lesser problems from gas production and migration then do sanitary landfills since dumps usually afford ample ventilation and organic content is reduced by burning. However, *any buried refuse whether in a dump or landfill may produce gases which may migrate to and accumulate in structures.*

Site Selection

To minimize gas production from landfilled wastes, they should be kept as dry as possible. Consequently, the site for a sanitary landfill should be selected so as to minimize entry of surface water or groundwater. Locations with high elevation, low water table and adequate natural surface drainage features are preferable. Sites should be selected so as to be least affected by nearby development which would increase surface runoff onto the landfill. To minimize effects of migrating gases, sites should be chosen which are remote from nearby existing structures or from likely future development on nearby land. The determination of proper separation between landfill sites and nearby development should be based on engineering evaluations, including gas permeability of soils. Sites in areas designated for open-space, recreational or similar nonconstruction uses are generally perferable, although adequate barriers can be constructed to permit on-site or nearby development in some cases. Sites should be selected so that the soil cover obtained on site will be sufficiently permeable to allow venting of gases through the cover, yet not so permeable that gases will easily migrate from the landfill periphery. Sandy soils and those with voids and rocks, etc. are likely to have high permeability for gas. Clay and similar soils would have low permeability. In general, sites should be selected which require a minimal amount of construction (such as surface drainage, barriers for gas controls, etc.) in order to minimize costs.

Landfill Design

A number of design features are important for the control of gases. If natural surface-drainage features are minimal, the landfill design should include a permanent surface drainage system to divert surface water away from the landfill. If groundwater levels are high, a membrane or other impermeable barrier should be required to exclude groundwater, or wastes should be deposited above ground. The landfill's final grade should be at least one percent to drain surface water without erosion of landfill soil cover. Landfill-edge slopes should also be protected against erosion. The operational plan should require adequate daily compaction and covering of incoming wastes so that voids are reduced and water entry during deposition is minimized. The area of solid wastes exposed to precipitation should be minimized by limiting the size of the working face. The design may also include installation of gravel-filled trenches, membranes or other permeable barriers or areas of undisturbed soil between waste deposits as natural barriers or vents (depending on soil permeability). The design should also stipulate the ultimate anticipated use of the completed landfill. If construction is to be permitted on site or nearby, developers should follow construction precautions to minimize potential for gas accumulation. Undisturbed areas of soil may be left for future building sites, utility conduits and roads. If soil permeability permits extensive lateral gas migration, it may be necessary to leave undisturbed an extensive peripheral area around each area where wastes are buried, within which building will be prohibited or restricted.

Landfill Construction and Operation

It is important that design and operational plans be closely followed during operation of the landfill and that any deviations therefrom be undertaken with caution and be recorded. In developing the landfill, it is important to minimize the proportion of the site which will be subject to receiving precipitation runoff and to conduct operations so that proper grade and cover will be restored as soon as possible. Natural cover and beneficial runoff characteristics should be retained as long as possible. Every effort should be made to insure prompt, maximum compaction and covering of the wastes within a minimal space. The highest and dryest portion of the site should be reserved for the placement of liquid and highly organic wastes, and they should be disposed so that surface drainage will be away from the main body of the deposited wastes. Absorption of liquids by spreading such wastes over the main body of drier wastes will serve only to accelerate gas production therein, over a wider area. Records should be kept on the location and character of special-waste deposition areas such as animal carcasses, sludges, etc., so that unusual gas-migration suspect areas will be demarcated. Such special-waste areas should be located in those parts of the landfill where on-site or nearby construction is least likely to occur. Such areas may be enclosed by impermeable or other gas migration barriers. Use of water for dust control should be kept to a minimum, and water should not be added to the wastes to aid in compaction. Pre-construction of trenches and stockpiling of cover materials should be minimized in order to reduce ponding of water and interference with proper drainage. Portable pumps should be used to drain ponded water rapidly, and finished areas of the landfill should be regraded and additional cover applied as necessary to eliminate ponding due to settlement and to restore cover integrity. Finished areas of the landfill should be revegetated as soon as possible in order to restore proper runoff, retain cover and stabilize slopes.

Ultimate Use

Development of the completed site should follow the designed plan. The finished site should be recorded in property records with a proper description of its conversion from prior condition to finished landfill, its intended use, zoning and use restrictions. Until ultimate-use plans are implemented, the finished site should be maintained so as to minimize water entry. Such maintenance will possibly include regrading, filling or revegetation of the site and the maintenance of surface or subsurface drainage.

GAS MONITORING PRACTICE

It has not been common practice to design or install systems at solid waste land disposal sites to detect or to measure the concentration of decomposition gases escaping from the surface of the landfill or migrating into adjacent areas. It has been shown that for landfills where initial or subsequent moisture in the wastes is limited, production and migration of gases will be relatively low and the need for monitoring gas migration will be minimal. Many landfills, particularly those constructed wholly or partially above original ground level, will have one or more edges, plus the landfill surface, exposed to the atmosphere, and monitoring will be required only where migration through adjacent soils will likely occur.

NEED FOR GAS MONITORING

For landfills where peripheral venting systems or barriers (active or passive) have been installed, monitoring needs will be minimal, and consist primarily of checking the effectiveness of the venting system or barriers. The principal need for monitoring will be at those landfills where:

(1) field saturation of the landfilled wastes occurs or is expected to occur at any time,

(2) subterranean utilities are installed nearby,

(3) buildings or other structures are constructed on or near the landfill (dependent on gas permeability of the soil),

(4) permit requirements or regulations require monitoring for migrating gases, or

(5) the landfill surface cover permeability is reduced by paving or other sealants, either during operation or following landfill closure.

Monitoring would not generally be required for landfills where ultimate use will be for open space, agriculture or other uses where utilities or enclosed structures will not be required. Suitable precautions should be taken, however, when and if utilities or structures are installed and in any instance where site-use plans are modified to uses which require on-site or nearby construction.

Those landfills whose cover materials are of high permeability will likely have high permeability soils adjacent, if the cover material was obtained on site. Nevertheless those landfills where adjacent soils are highly permeable to gas flow are most in need of monitoring. Even though the landfill will likely vent gases rapidly through the permeable cover, surface water may easily infiltrate the cover to expedite gas production. Periodic saturation of the soil cover will at least periodically reduce cover permeability for brief periods, possibly resulting in brief subsequent episodes of lateral gas migration. Consequently, gas monitoring will likely be most important following heavy precipitation episodes.

In those instances where landfills have highly permeable soil cover but relatively impermeable surrounding soils or impermeable barriers, there will be minimal need for gas monitoring.

It has been noted that landfills will produce decomposition gases, particularly methane, for 30 to 40 years. Also if conditions change, such as introduction of groundwater or surface water, so that moisture increases occur in a formerly dry landfill, gas production may be reinitiated. Consequently, it cannot be safely assumed that a vintage landfill will no longer produce gas, and some form of monitoring or surveillance may be required indefinitely.

PHYSICAL OBSERVATIONS

The operator or manager of a solid waste land disposal facility, or those examining a site with regard to ultimate use or nearby construction can, through observation of some physical features, sometimes gauge the potential for gas migration or detect signs of gas migration occurring. Recording of such observations during the active lifetime of a sanitary landfill will provide some guidance to future development of gas migration problems. Physical observations, performed without dependence on expensive instruments, may serve as an early warning of potential problems from gas migration which can be followed up with instrumented surveillance. Early warning signs of potential problems include observation of unusual settlement, effects on vegetation, occurrence of gas in sewers or other subterranean structures (which may require instrumented surveillance), odors or gas bubbles in water accumulations. Observations on these phenomena at the Link Road facility, as related to gas production and migration, are noted in the following sections.

Settlement

Whereas the surface of the Link Road landfill is generally flat, a number of random undulations occur throughout, indicating that local settlement has occurred. Over most of the landfill, the settlement observed was similar to that occurring in most landfills of its type (i.e., moderate but not extensive). Two specific areas of extensive and dramatic settlement were in the area just back of the Armory where wastes were deposited along a steep natural bank and in the fire training area. The peripheral road is undulating, indicative of settlement throughout. Just above the lower peripheral road, large depressions were overgrown with cattails (a water-loving plant) and after rains, all depressions held water for long periods of time. Similar cattail and water-filled areas were noted just north of the concrete slab back of the Armory. Extensive cracking of the soil cover was noted in the fire training area and in a line paralleling the bank crest back of the Armory, indicative of settlement and local infiltration of surface water.

After new cover was applied in the summer of 1973, it was noted that rapid settlement was continuing back of the Armory and that a crack was re-established along the bank crest.

Settlement plates placed throughout the fill were lost when the new cover was placed, and only a minimal amount of settlement was noted for the few months they were in place. The landfill is settling slowly in general, but rapidly in a few locations. The settlement areas are generally characterized by relatively high combustible gas concentrations. The rate of settlement immediately prior to the Armory explosion and the effect of settlement in increasing gas migration at that time could not be established. Obviously, the rate of settlement in the fire training area and in the area back of the Armory is much faster than nearby areas of the landfill.

As at Link Road, rapid-settlement areas in most landfills are often those where the highest gas concentrations occur. Where settlement is the result of rapid decomposition of wastes in the immediate area, rapid gas evolution is to be expected and its migration through nearby soils results both from internal pressures caused by shifting of the mass and from increasing gas pressure. Additionally, channels may be created through disruption of cell integrity, soil-cover displacement and erosion processes by surface water entry through which gas escapes readily. These processes are likely all combined in the Link Road landfill's fire training area.

In the settlement area back of the Armory, the deposited wastes are not likely to produce gas at as high a rate as those in the fire training area because the wastes placed near the Armory were less putrescible. Consequently, the settlement is likely due to physical causes, primarily the sliding of the wastes down the natural slope, hastened by the entry of water from ponding and cracking and the weight of additional cover material. From these observations, it can be confirmed that settlement areas in landfills are likely locations where gas is rapidly being generated or gas migration is being hastened and abetted by physical processes. In either situation, observations of settlement are a means of discerning locations of high gas migration potential for further observation.

Visual features associated with settlement areas include, in addition to the differences in elevation, which may not be apparent for moderate settlement, specific types of vegetation and surface cracking. Water-loving vegetation such as cattails may grow in settlement areas which frequently hold water. In grassy areas, grass does not grow in the immediate vicinity of the crack so that cracks in the soil cover are readily visible when the grass is short and dormant but are less visible when the grass is long or growing vigorously.

Vegetation

A preliminary assessment was made at the Link Road landfill of the potential for visual effects of gas damage to vegetation serving as a monitoring aid for detection of gas migration. A report of this assessment is included in Appendix B.

Vegetative growth at the Link Road landfill was heterogeneous but had no apparent correlation with areas of high or low gas concentration (neither was there a discernable pattern of gas concentration at the landfill surface indicating consistently high and low gas concentration areas). Vegetation at other landfills in the area was either too sparse or too recently established to permit meaningful observations.

Areas peripheral to the Link Road landfill where gas data were available were not vegetated, being covered with either asphalt or crushed stone.

The one area where visible effects on vegetation were noted was in the fire training area. It appears that in the immediate vicinity (one to two inches) of a crack from which gas is emerging, vegetation does not grow. This effect may be due to the drying effect of the gases in the grass' root zone. On either side of the bare area along the cracks, the grass appeared to be growing well, with no gradation in color or growth rate being observable. Grass (fescue) at the Link Road landfill is apparently not a sensitive vegetative indicator of gas migration. Nevertheless, plantings of grass on the perimeter of a landfill and into adjoining areas might aid in increasing the visibility of any cracks or openings in the surface from which gas may be emerging.

In some areas, it has been reported that certain ornamental plants have been killed by gas migrating from landfills and that it is difficult at some landfills to maintain grass cover or plantings because of gas. The potential for gross observation of effects on vegetation to serve as an indicator of gas migration remains undefined.

Other

It has been noted in the literature that at some landfills, bubbles of emerging gas can be noted in surface-ponded areas after a rain. This phenomenon was noted by one observer at the Link Road landfill in the ponded water filling settlement depressions in the fire training area.

In general, occurrence of a local strong concentration of odor might be taken as an indicator of gas migration, but it would likely be difficult to distinguish the precise location or to gauge the concentration. Methane is odorless and could not be detected in this manner. Other gases may lose a characteristic odor on passage through soil. No localized odor concentrations were noted in the proximity of high gas concentration areas at the Link Road landfill, or from cracks where gas was known to be emerging at high concentration.

The detection of gas by physiological response is unreliable. While a premonition of gas accumulation in the Armory's supply room was evidenced by occupants' citing "odors" and "choking" sensations, such phenomena could not be verified by observers.

At some landfills, pipes fitted with burner devices have been inserted through the cover and gases have been flared. Such devices installed in nearby soils might indicate, by ignition, the presence of relatively high combustible gas concentrations, but a periodic ignition source would be required. Burning of emerging gas is less effective than barriers as a means of curtailing gas migration.

INSTRUMENTED SURVEILLANCE

Gas concentrations at the Link Road landfill were determined through instrumented surveillance, taking gas samples from installed probes. A review of these procedures and findings follows.

Gas Probe Layouts

A series of probes were installed at the Link Road landfill and at two other landfills in order to determine gas concentrations. The probes were of the Los Angeles type (Reference 23), consisting of a short length of perforated plastic tubing attached to small-diameter plastic tubing. The probes were placed at various depths (1, 10 and 25 feet, normally) in six-inch diameter holes at various sampling locations, and the holes were back-filled with soil (between probe placements) to the ground surface. Each probe tubing lead was marked according to probe depth. For the earlier studies, probes were established around the Armory. Later, additional sampling locations were installed on a grid patter, extending several hundred feet outward in the landfill. In many of these locations, water was encountered within two to three feet of the landfill surface. Upon installation of the gas barrier, additional sampling locations were established on either side of the barrier. In addition, well-point-type probes were established inside the barrier and connected to the gas monitor. Four occupied-space interior probes were connected to the monitor installed inside the Armory. The various probes and their locations are described in Figures 5, 6, 14 and 15.

In order to determine pressure differentials in the soils along the barrier and between wells, 10 sampling locations (Figure 15) were established along a portion of the barrier back of the Armory supply room. Probes were established at two depths at each location, and pressure readings were taken by use of a mobile manometer (Figure 16).

Instrument Use

Two portable combustible gas detectors (J-W Gas Kit, Model HPK) were used to determine gas concentrations from the probes at each sampling point. This instrument is calibrated to show combustible gas concentrations in percent by volume in air. In use, the operator inserts the instrument's metal probe into the probe tubing at the sampling point and permits the instrument's vacuum pump to evacuate the tubing until a proper sample is obtained. The steady-state concentration reading is recorded for each probe and sampling station. During the studies, concentrations were determined daily in some instances, and at weekly intervals on others. The instrument was calibrated against standard gases and was checked for "zero" (atmospheric) readings frequently.

In addition to the gas concentration data obtained by use of the portable gas detector, samples were also analyzed by gas chromatography. Samples were obtained from the probes by using evacuated flasks connected to the probe tubing, following evacuation of the tubing with the portable instrument's vacuum pump.

SIGNIFICANCE OF FINDINGS

Sampling Pattern

The distance between sampling stations ranged from about 10 to over 100 feet. The original series was dispersed in accordance with the need to establish gas concentration profiles around the Armory, with closest spacing nearest the Armory supply room. Outlying sampling points were established to determine concentrations in presumed high gas areas (such as those in the fire training area) or to determine the boundaries or extent of gas migration potential. Shallow probes of one-foot depth were established to determine if gas was emerging through the soil surface, whereas the deep probes were established at the approximate level equivalent to the base of the landfill.

In general, the concentrations at the lowest probe of a sample location were highest while those at mid-depth were somewhat lower. Concentrations at the one-foot probes were erratic and are considered unreliable.

Gas Migration

Typical combustible gas concentration profiles are shown in Figures 6, 17 and 18.

Gas concentrations in the landfill were generally only slightly higher than those in probes between the landfill and the Armory, indicative of the relative ease with which gas migrates through the peripheral soil. Concentrations above the LEL were noted in the parking lot northeast of the Armory at considerable distance from the landfill; but north of the Armory, concentrations were at zero levels.

The findings indicate that gas migrates readily to the Armory and at considerable distance from the main landfill across the former incinerator-residue area. Where the gas apparently encounters undisturbed soil, as at the northern boundary of the fire training area, the undisturbed soils near the front of the Armory and the parking area southeast of the Armory, it is more rapidly attenuated. These areas, however, are at considerable distance from the landfill boundary, and attenuation may be attributed as much to distance as to decreasing soil permeability.

The gas samples consisted primarily of methane, as the gas chromatographic analyses attests (Tables 10 and 11).

Gas production and migration from the Link Road landfill continues year-round at a significant rate, though it is steadily declining. At the present rate, significant gas production may continue 10 years or more. Seasonal variations in gas production and migration have been noted, with peaks occurring in February or March and declining through the summer months to lows in mid-winter. Combustible gas concentrations in the 40-percent range are still occurring near the landfill boundary, and explosive-concentration accumulations are a potential for years to come. There appears to be a short-range increase in gas migration occurring after rainfall episodes; consequently, there is a need to be concerned with gas migration problems at this site on a relatively continuous basis.

The Link Road landfill seems to have the following characteristics, with regard to gas migration and explosive hazards:

(1) the landfill is largely saturated and is producing methane gas steadily with both seasonal peaks and periodic increases following precipitation episodes;

(2) gas migrates readily through the soil to nearby structures, due to high gas permeability of the intervening soil;

(3) major structures are in close proximity to the landfill or are built on site and until recently have had no means to prevent gas entry;

(4) major settlement is continuing to occur in areas of the landfill closest to structures and permeable soil strata; and

(5) gas migration appears to be attenuated below the LEL within 200 feet of the landfill boundary when passing through undisturbed soil.

It appears likely that despite the high production of gas at this site and the relatively permeable nature of the soil, normal building construction could have been followed for structures built on natural ground 100 to 200 feet from the landfill boundaries (though not on the incinerator-residue portion).

GAS DETECTION

Observations in Subterranean Structures

In retrospect, the occurrence of the flash fires in sewer drains and roof gutters could have served as advanced warnings of gas migration. In fact, the fires in the sewers of the fire training area were assumed to be associated with the entry of landfill gas. Occurrence of gas in sanitary sewers, as noted in a later investigation, is less definitive. Rapid settlement in both heavy-settlement areas was noted, but its possible relation to lateral gas migration was not suspected. There were no observed effects on vegetation indicative of gas migration or of gas bubbles in ponded water.

Physical Phenomena

At this site, physical phenomena related to gas migration were either not of sufficient magnitude, could not be properly observed or were associated with factors not related to gas migration to the Armory.

Instrumented Surveillance at Shallow Depths

It has been suggested that sampling for gas with a portable instrument at shallow (1 foot) depths in the soil adjacent to a landfill boundary could serve as an early warning of gas migration. The erratic nature of data from the one-foot probes in the initial gas sampling network indicates that this is an unreliable procedure *per se*. It was observed that any sampling from an unclosed system wherein air may be entrained with the gas sample gives erratic results. Any such system should be based on the sampling of permanently installed probes installed at least three feet below the surface.

Sampling Patterns

The placement of sampling stations to monitor gas migration should be based on some knowledge of the soil permeability. If gas permeability tests of peripheral soils indicate low permeability, it would probably suffice to place sampling stations at 100-foot intervals along and 25 to 50 feet from the landfill edge. At landfills adjoined by highly permeable soils, stations should be at 50-foot intervals or less with a second line of stations 100 feet from the landfill edge. The nature and extent of the pattern will depend in large measure on the gas permeability of the soil and proximity of the facilities to be protected. Intervals suggested herein are admittedly arbitrary. At landfills where peripheral soils are relatively impermeable, it might only be necessary to install monitoring probe networks in the near vicinity of areas of the landfill where high gas production is anticipated (i.e., wet-waste disposal, sludge disposal, animal carcass disposal, etc.). In general, where the likelihood of gas migration is greatest and the resultant hazards are most significant, the gas monitoring network should be of greater sophistication.

ROUTINE OBSERVATIONS

Relatively simple observations should be required of landfill operators to provide early warning of potential gas migration. These include recording:

(1) occurrence of rapid or extensive settlement;

(2) occurrence of extensive cracking in landfill cover or nearby soils;

(3) occurrence of vegetation browning or die-off in peripheral areas;

(4) concentration of odors;

(5) occurrence of flash fires or minor flares on or off site; and

(6) occurrence of bubbles in ponded water on landfill periphery.

INSTRUMENTED OBSERVATIONS AND RECORDS

If any of the crude observations or a combination thereof indicates that gas migration may be occurring, landfill supervisors should institute surveillance based on use of portable gas detectors and relatively shallow, but permanently installed, probes. This should include:

(1) installation of a suitable probe network in the suspect areas, probes being established at least three feet deep; and

(2) sampling and recording combustible gas, using a portable gas detector, according to the following schedule:

  (a) weekly, during spring and early summer;

  (b) daily following heavy precipitation; and

  (c) at regular two-week or monthly intervals during winter and fall months.

FOLLOW-UP GAS MONITORING

If concentrations are found near the explosive range, additional probes, placed at 10- to 15-foot depths will aid in determining the extent and range of gas migration. The range of probe placement should be extended if gas concentrations continue to occur at the outer edge, in order to determine extent of migration. If levels continue or are in the high range, it will be necessary to consider barrier installation or prohibition of construction within the near vicinity of the landfill.

GAS MONITORING INSTRUMENTS

Relatively simple, low-cost portable gas detectors are available which indicate presence of combustible gas and are calibrated to read gas concentrations in percent of the lower explosive limit (LEL). Gas readings near or in excess of the LEL (5% by volume of methane in air) would indicate the possible necessity of follow-up monitoring, using a more expensive portable instrument calibrated to read higher combustible gas concentrations directly in percent by volume.

Instruments of this type are commonly used by utility companies, public works departments and fire departments. Arrangements could probably be made with such agencies for routine monitoring and reporting of gas concentrations in subterranean facilities near landfills.

Gas samples can be taken from inexpensive subsurface probes in evacuated flasks for gas chromatographic analysis in commercial laboratories. Many water and sewer department laboratories can perform such analyses at minimal cost.

SUMMARY

In summary, careful selection, design and operation of sanitary landfills will usually minimize gas production and migration. Gas production and emergence through soil cover is to be expected in a sanitary landfill, but on-site or nearby structures should be protected from gas migration or accumulation by structural features, distance or by passive or active gas barriers.

During landfill operation, careful observation and recording of physical features such as settlement, damage to nearby vegetation, flash fires, odor occurrences, gas in subterranean facilities, etc. will provide early warning of potential gas migration. Use of portable gas detectors to sample combustible gas concentrations from permanently installed probes can verify gas migration problems, and follow-up monitoring with more sensitive instruments will aid in the decision to control gas migration or restrict use of the area of gas migration.

Observations at the Link Road landfill verified the utility of settlement and subterranean-facility gas determinations as indicators of gas problems but did not afford opportunity to verify utility of vegetation effects as a gas migration indicator. Shallow sampling of soils with a portable gas detector is unreliable. Probes three to 10 feet deep will provide reliable indication of gas movement. Gas production and migration at the Link Road site peaked in the spring months, declined through the summer and increased through the fall months.

Monitoring of landfill gas migration should be based on soil permeability, proximity of nearby structures and knowledge of the location and extent of high gas production areas. In some landfills, monitoring may be restricted to known high gas production areas.

CHAPTER X

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APPENDIX A

COST ESTIMATES FOR FORCED VENTILATION, NATURAL VENTILATION AND IMPERMEABLE MEMBRANE GAS CONTROL SYSTEMS

PRELIMINARY COST ESTIMATES FOR FORCED

VENTILATION GAS CONTROL SYSTEMS
(dollars)

Item	High-flow system	Low-flow system without seal	Low-flow system with seal
18 Gas wells[a]			
Construction	13,500	13,500	13,500
Butterfly valves	2,500	2,500	2,500
Fittings	1,000	1,000	1,000
Precast boxes	6,100	6,100	6,100
Suction header			
Pipe, fittings, etc.	8,900	2,500	2,500
Vacuum pump & fittings			
Pump, valves, electrical panels, flame traps, etc.	16,000	8,000	8,000
Surface seal	--	--	36,000
Contingency	4,000	4,000	4,000
TOTAL	52,000	37,600	73,600

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[a] Includes 15 wells in the main branch and three wells in the small branch of the gas control system.

COST CALCULATIONS FOR NATURAL VENTILATION AND IMPERMEABLE MEMBRANE GAS CONTROL SYSTEMS*

ASSUMPTIONS

The following assumptions were made for calculating capital costs of the natural ventilation and impermeable membrane gas control systems:

(1) A dragline can excavate 81.6 yd^3/hr at the rate of $45/hr.

(2) A 20 feet deep trench 2 feet wide can be excavated for the natural ventilation system.

(3) Gravel will cost about $2.25/ton delivered on site.

(4) A side slope of 1.5 vertical to 1 horizontal will be required for impervious membrane trench when clay is used as the barrier material.

(5) The impervious membrane will consist of a dry core 2 feet wide and 20 feet deep.

(6) Clay will cost $4.25/ton delivered on site.

(7) Clay tamping will cost about $0.80/$yd^3$.

(8) Clay and gravel have a density of 2.20 ton/yd^3.

COST BREAKDOWN

Natural Ventilation System

Excavation cost	=	$ 800
Gravel materials	=	7,400
Other costs	=	1,800
Total costs		$10,000

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[*] Costs will vary somewhat, by location

Impermeable Membrane

Excavation cost	=	$ 6,200
Clay materials	=	14,000
Clay tamping	=	1,150
Other costs	=	3,200
Total costs		$24,550

VOLUME CALCULATIONS

Natural Ventilation

1,000-foot trench x 20 feet deep x 2 feet wide = 40,000 ft^3

Trench volume = 1,480 yd^3

Impermeable Membrane

1,000-foot trench x 20 feet depth x 15.32 feet average width for side slope of 1.5 vertical to 1 horizontal

Total volume = 306,400 ft^3 = 11,400 yd^3

Clay volume = 40,000 ft^3 = 1,480 yd^3

APPENDIX B

EVALUATION OF EFFECTS ON VEGETATION REGARDING SANITARY LANDFILLS AT WINSTON-SALEM, NORTH CAROLINA

Report
to Engineering-Science, Inc.
on the
Detailed Work Plan
for
Evaluation Effects on Vegetation
Regarding
Sanitary Landfills
at
Winston-Salem, North Carolina

19 April 1973

Gayther L. Plummer, Ph.D.
995 Timothy Road
Athens, Georgia

The purpose of the work plan was to "Obtain and Review Data on Effects of Gas on Vegetation."

A general perusal of the work plan gives the initial impression that the project is well conceived, well organized, having clearly defined objectives, good control characteristics, and the problem to be solved is simple, straight forward with potentially clear-cut results. The problem looks challenging partly because the nature of the objectives have an intriguing origin and partly because the concept of identifying sentinel plants to indicate an impact of mankind on the environment is relatively underfined.

The work plan calls for the derivation of diversity indices to relate to gas potentials and to effects on sentinel plants. This part of the work plan seemed to have some inherent difficulties built into it having been designed without first-hand knowledge of the way diversity indices are interpreted based upon field conditions. To devise the indices would be no problem, but to relate the meaning of that information to the objectives of the project are obstacles that appeared to be difficult to achieve.

A trip to Winston-Salem, North Carolina, and to the landfills was undertaken in conjunction with a student in the Botany Department at the University of Georgia to determine the feasibility of completing the work plan to the satisfaction of Engineering-Science, Inc. We went on the weekend of 6-8 April 1973. A day and a half were spent in the field. Both the Link Road site and the Overdale sites were visited under the guidance of Mr. Robert Davis.

Communications with Engineering-Science, Inc. advised me that methane gas was a principal component of those emitted from the old city dump. A very brief search of the literature revealed also that carbon dioxide, hydrogen, sulfur dioxide, and hydrogen sulfide were among the possible kinds. The effects of gas on vegetation would be complicated, therefore, by mixtures of gases of unknown composition and of unknown concentrations. At the site it was easy to learn that age of the fill and time differences in decomposition rates were added complications.

The soil was cracked in placed, sometimes around subsidence pits, so gases immerged from place to place according to the distribution and kinds of subterranean materials.

Vegetation on the old city dump also varied from place to place. Some was of the one-year-old abandoned field type, that is crabgrass and ragweed stems. Others were of the six- to eight-year-old field type--Golden rods, Asters, etc. Yet others, wetland Cattails, and dryland Broomedge grass, grew side by side--an unnatural situation brought about by physical changes in the level of the land. Diversity indices related to site quality are not meaningful indicators of effects of gas on vegetation.

Gas oozed from pools of water in the pits as out body weights shifted from place to place. It became conclusive, therefore, that changes in atmospheric pressure of one inch could change the load factor on gas emission by approximately two tons in a pit covering about 300 square feet. This means that cloudy weather and a pressure drop would probably cause gases to accumulate internally whereas sunny skies and high pressures would cause these gases to be forced out.

Soils differed greatly within one square meter. Some places the clayey soils were tough enough to exclude all root penetration; in other places the sandy soils allowed good plant growth. Chalky alkali sites evidently excluded some species. High nitrogen places occurred, as did nitrogen-deficient sites.

Within the chain-linked fence at the Link Road site, the fescue grass was growing poorly in some places and excellently in others. It seemes to have been planted uniformly. It also seemed to have been affected by poor growth in a small area where odors of certain gases were almost suffocating to us. Bermuda grass, however, grew very well where fescue did not. The ground was cracked in placed, odors came from the cracks, and all grasses within four to five inches on each side of the cracks were dead. This small situation (and there were several lines of such features) was the only place in which vegetation was obviously affected by something that came apparently from the cracks.

Otherwise, there was absolutely no doubt that soil textures and fertility were responsible for most other variations in the vegetation. The certainty of harmful effects of gas along these cracks cannot be demonstrated clearly without further study.

One plant, the Chickweek, was yellowed in certain situations but not in others. Careful examination showed that the lower leaves were in fact dead. Other leaves had yellow spots on them similar to such defects as those caused by sulfur dioxide in other plants. This sign of yellowness suggests the possibility of a sentinel plant. Because the manifestations were very localized and not widely spread raises some doubts about the real indicator values of such "effects." There is no doubt in my mind that other plants can be affected similarly, and probably are. But the interpretation and meaning of these facts must be tested under experimental conditions before any useful indicator values of sentinel plants can be suggested more particularly. To compare these effects with concentrations of gases in the field would be nearly impossible, especially without knowledge of the way in which a single kind of gas injures a plant species. The hopeful thing about all this is that detrimental effects do occur, but they do not seem to be widely spread.

The assumption all along seems to be that detrimental effects are the chief manifestations of gas concentrations. Perhaps this stems from Crocker's bood Growth of Plants in which the affects of gases on plants are treated as extensively as was knowledge about the subject until 1948. On the other hand, beneficial effects could be possible because methane fumes are known to stimulate the growth of potato buds (see Biol. Abst. 1972, item 33720). Marsh gas, of which methane if the prime constituent, is commonly associated with plants. No doubt many plants have become quite tolerant to methane. Hydrogen sulfide is not really very toxic to plants, but it is to animals. A very good possibility exists that the vegetation on a sanitary landfill, or any old dump, could be enhanced in places by the totality of the local environment.

The Overdale site is a marvelous example of what landfills ought to be. The fescue plantings added acceptability of the site. That grass did have several unusually green patches growing here and there--probably from dung piles dropped by stray dogs, perhaps urine spots, etc. In general, the grass looked nitrogen deficient, but uniformly so. Obviously, the site was more homogeneous than the old dump. No detrimental conditions were outstanding. The question was raised: What sentinel plants would indicate gas at different concentrations here? The assumption was either that gases would ooze from the ground uniformly, or that they would move laterally and come out near some pre-existing barrier.

A search for such a plant is underway. Perhaps one can be found, such as Chickweed, but it is more likely to be an annual rather than a perennial; it would probably be a temporary rather than permanent resident on the site; and it would be seasonal in its responsive indicator qualities. When that plant, or plants, are found then growth responses are needed to indicate sensitivity to specific concentrations of a particular gas causing the effects.

In this case a chemical indicator of gas seems to be more feasible and more reliable than indicator plants. Plants have more variability in growth characteristics to be equally valuable and equally reliable all year long. Actually, several species would be necessary to function as sentinels regularly.

In summary, there is no doubt that vegetation, or plant species in particular, can be affected either detrimentally or beneficially by environmental conditions within an old city dump. To relate any affects to the natural gases from anaerobic aeration within the soil, and to separate effects of gases from other effects induced by soil conditions, would be essentially a major undertaking involving rather rigidly-controlled site conditions. The expense of searching for sentinel plant species, followed by the testing of suspect populations, and the actual use of them in a realistic set of field conditions requires time and efforts that might well be spent in search for a chemical indicator whose reliability is more certain, dependable and enduring.